


34th International Geological Congress (IGC)

Brisbane Convention and Exhibition Centre, Queensland, Australia

5 - 10 August 2012

Unearthing Our Past And Future – Resourcing Tomorrow

Q-11 ***11 - 16 August 2012***

North Queensland: 1700 million years of Earth History on the Proterozoic-Phanerozoic Margin of Eastern Australia

Mr Ian Withnall and Professor Bob Henderson

North Queensland: 1700 million years of Earth History on the Proterozoic–Phanerozoic Margin of Eastern Australia

by

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ISBN 978-1-922067-09-8

August 2012

BIBLIOGRAPHIC REFERENCE:

Withnall, I.W. & Henderson, R.A., 2012: North Queensland: 1700 million years of Earth History on the Proterozoic–Phanerozoic Margin of Eastern Australia. 34th International Geological Congress, post-congress field excursion guidebook.

Contents

Field trip Itinerary

Day 1 (Saturday 11 August 2012)

Registrants make their way to Cairns and check in to the Pacific International Hotel.

2:00 – 5:00	An optional trip along the coast to the north of Cairns may be possible

Day 2 (Sunday, 12 August 2012)

8:30	Depart Cairns
9:15 – 9:45	Stop 1: Barron River Falls, Kuranda:
11:30 – 12:00	Stop 2: Abandoned Thornborough townsite: turbidites of the Hodgkinson Formation
12:30– 1:00	Stop 3: Near Kingsborough townsite: mélange in Hodgkinson Formation
1:15 – 2:30	Lunch and tour at historic Tyrconnel mine
3:45– 4:15	Stop 4: Burke Developmental Road: rhyolitic ignimbrite of Carboniferous Featherbed Volcanic Group
4:45 – 5:00	Stop 5: Burke Developmental Road: granite of the Kennedy Igneous Association
5:30 – 6:00	Visit to historic smelter site
6:00	Overnight – Chillagoe

Day 3 (Monday 13 August 2012)

8:00	Depart Chillagoe
8:15 – 9:00	Stop 6: Balancing Rock, Chillagoe: Silurian to Early Devonian limestone of the Chillagoe Formation, including some indigenous rock art
9:30 – 10:00	Stop 7: Dargalong Metamorphics, Chillagoe-Bolwarra road
12:30 – 1:30	Stop 8: Hypipamee Crater and lunch
2:30 – 2:45	Stop 9: Innot Hot Springs
4:30 – 5:15	Optional Stop 10a: Kilkani Cone
6:00	Overnight – Mount Surprise

Day 4 (Tuesday 14 August 2012)

8:30	Depart Undara Lodge
8:30 – 10:00	Stop 10: Undara National Park: tour of volcanic features including lava caves
11:00 – 11:30	Stop 11: Eastern side of Newcastle Range on Gulf Developmental Road: faulted contact between Newcastle Range Volcanic Group and Silurian White Springs Granodiorite.
11:45 – 12:15	Stop 12: Routh Creek, Newcastle Range on Gulf Developmental Road: Carboniferous ignimbrite of the Newcastle Range Volcanic Group.
12:30 – 12:45	Stop 13: Gulf Developmental Road, west of the Newcastle Range: Silurian White Springs Granodiorite.
1:00 – 1:45	Lunch – Georgetown
2:00 – 2:30	Stop 14: Quartz Blow Creek: S-type Mistletoe Granite
3:00 – 3:30	Stop 15: Forsayth–Georgetown road: Forsayth Granite
4:00 – 5:00	Ted Elliott Mineral Display – Georgetown
5:00	Overnight – Georgetown

Day 5 (Wednesday 15 August 2012)

8:00	Depart Georgetown
8:45 – 9:15	Stop 16: Western Creek – andalusite schist, Paleoproterozoic Lane Creek Formation
9:30 – 10:00	Stop 17: Western Creek – Paleoproterozoic Cobbold Metadolerite
12:00 – 1:00	Stop 18: Lunch at Copperfield Gorge at Einasleigh township: Quaternary basalt (opportunity to visit Einasleigh Hotel)
1:00 – 1:45	Stop 19: Einasleigh River at old copper mine: gneiss and amphibolite of Einasleigh Metamorphics and Carboniferous microgranite ring dyke
2:45 – 3:15	Stop 20: Einasleigh – The Lynd road near ND Creek: Neoproterozoic or Cambrian Oasis Metamorphics (east of Tasman Line)
3:30 – 4:00	Stop 21: Lynd Highway, south-east of The Oasis: Balcooma Metavolcanics
4:30 – 4:45	Stop 22: Lynd Highway, west of Greenvale: chloritic schist of the Cambro-Ordovician Eland Metavolcanics
5:00 – 5:30	Stop 23: Access road to Greenvale Nickel mine: Neoproterozoic or Cambrian schists of the Halls Reward Metamorphics and serpentinite of the Boiler Gully Complex.
5:30 – 6:00	Stop 24: Lynd Highway, east of Greenvale: Judea Formation
6:00	Overnight – Greenvale

Day 6 (Thursday 16 August)

7:30	Depart Greenvale
7:45 – 8:15	Stop 25: Spring Creek causeway on Greenvale–Wandovale Road: Gray Creek Fault Zone separating Cambrian (?) mafic–ultramafic Gray Creek Complex (amphibolite) from Late Ordovician Carriers Well Formation
8:30 – 9:00	Stop 26: Dinner Creek on Greenvale–Wandovale Road: Volcaniclastic turbidites of the Carriers Well Formation
9:30 – 9:45	Stop 27: Cutting on the Gregory Highway, about 1 km east of Greenvale township, Wairuna Formation
10:15 – 10:20	Stop 28: Gregory Highway, about 46 km from Greenvale, limestone olistostromes in the Perry Creek Formation
10:30 – 12:00	Stop 29: Clarke River, Lynd Highway: turbidites in the Early Devonian Kangaroo Hills Formation (including early lunch)
12:15 – 12:30	Stop 30: Fullstop turnoff, Lynd Highway: conglomerate of the Clarke River Group
1:00 – 1:15	Stop 31: Ewan Racecourse, Lynd Highway: Cambrian (?) Argentine Metamorphics
2:15 – 2:30	Stop 32: Gregory Highway, 6 km north of Charters Towers: Charters Towers Metamorphics
2:45 – 3:30	Stop 33: Towers Hill Lookout, Charters Towers
3:30 – 5:00	Travel to Townsville
5:00 – 5:45	Stop 34: Castle Hill, Townsville: rocks of the Permian Kennedy Igneous Association and coastal physiography
6:00	Tour concludes

Introduction

The post-congress field trip will depart Cairns and travel through the Paleozoic Hodgkinson Province to Chillagoe, which is near the province-bounding Tasman Line, a major north–south structure that extends through eastern Australia, and separates largely Paleozoic rocks from the Paleoproterozoic to Mesoproterozoic rocks to the west. The excursion then visits sites of some of Australia's youngest volcanism, part of an intraplate alkali basalt assemblage, before examining rocks of the Paleoproterozoic to Mesoproterozoic Etheridge Province. The excursion will then cross back over the Tasman Line, visiting Paleozoic sediments and early Paleozoic metamorphic rocks and granitoids of the Greenvale, Broken River and Charters Towers Provinces before ending in Townsville. Much of the excursion route follows deep seismic traverse lines shot in 2007, interpretation of which provides a perspective of deep crustal structure in relation to surface rock assemblages.

The excursion will be led by Ian Withnall (Geological Survey of Queensland) and Bob Henderson (James Cook University). An overview of the geology of the region was given by Withnall & Henderson (2012) and more detailed descriptions can be found in papers in the *North Queensland Geology* volume by Bain & Draper (1997) and the forthcoming *Geology of Queensland* volume edited by Jell (in press). Additional references are given in this guide, but are not intended to be exhaustive.

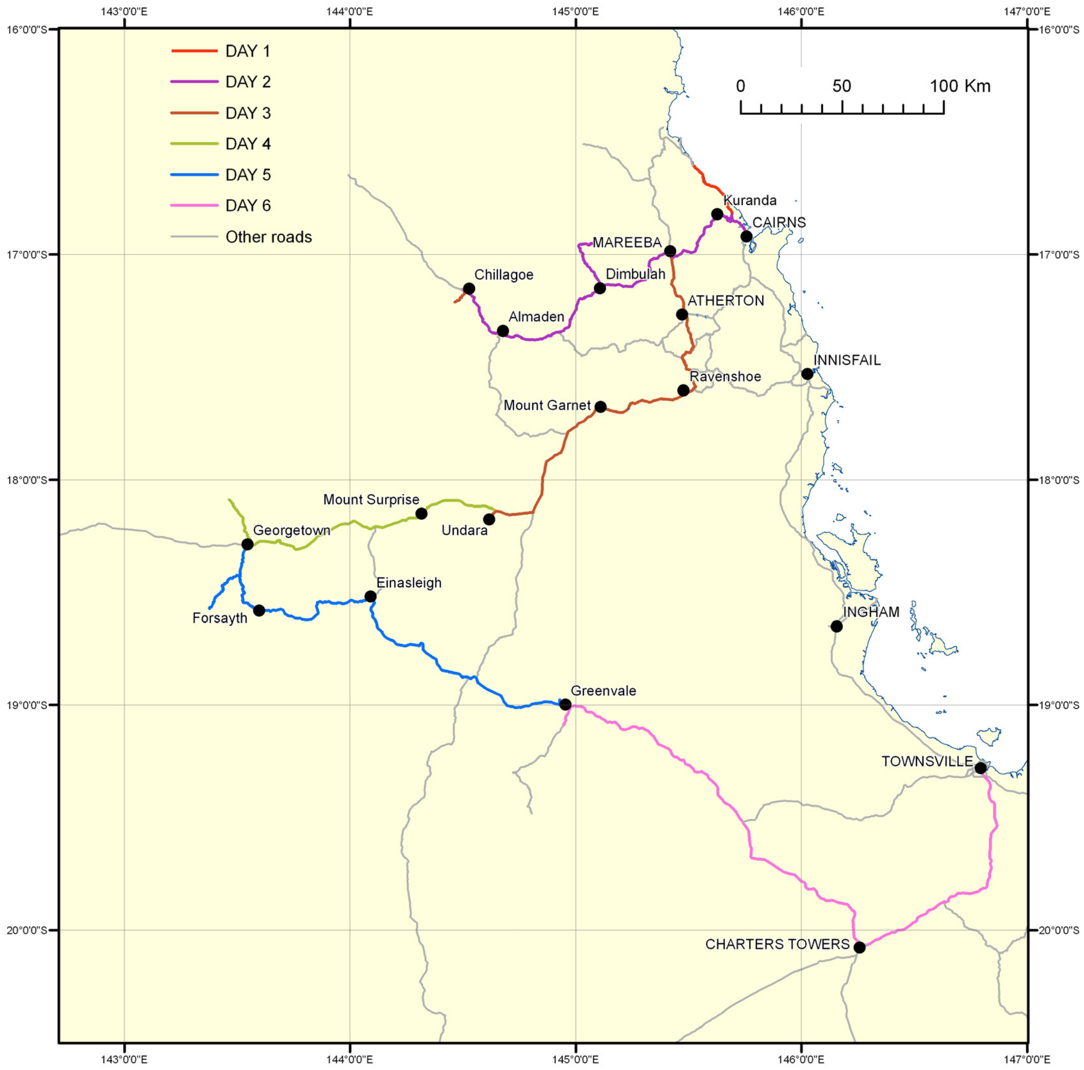


Figure 1. Excursion route

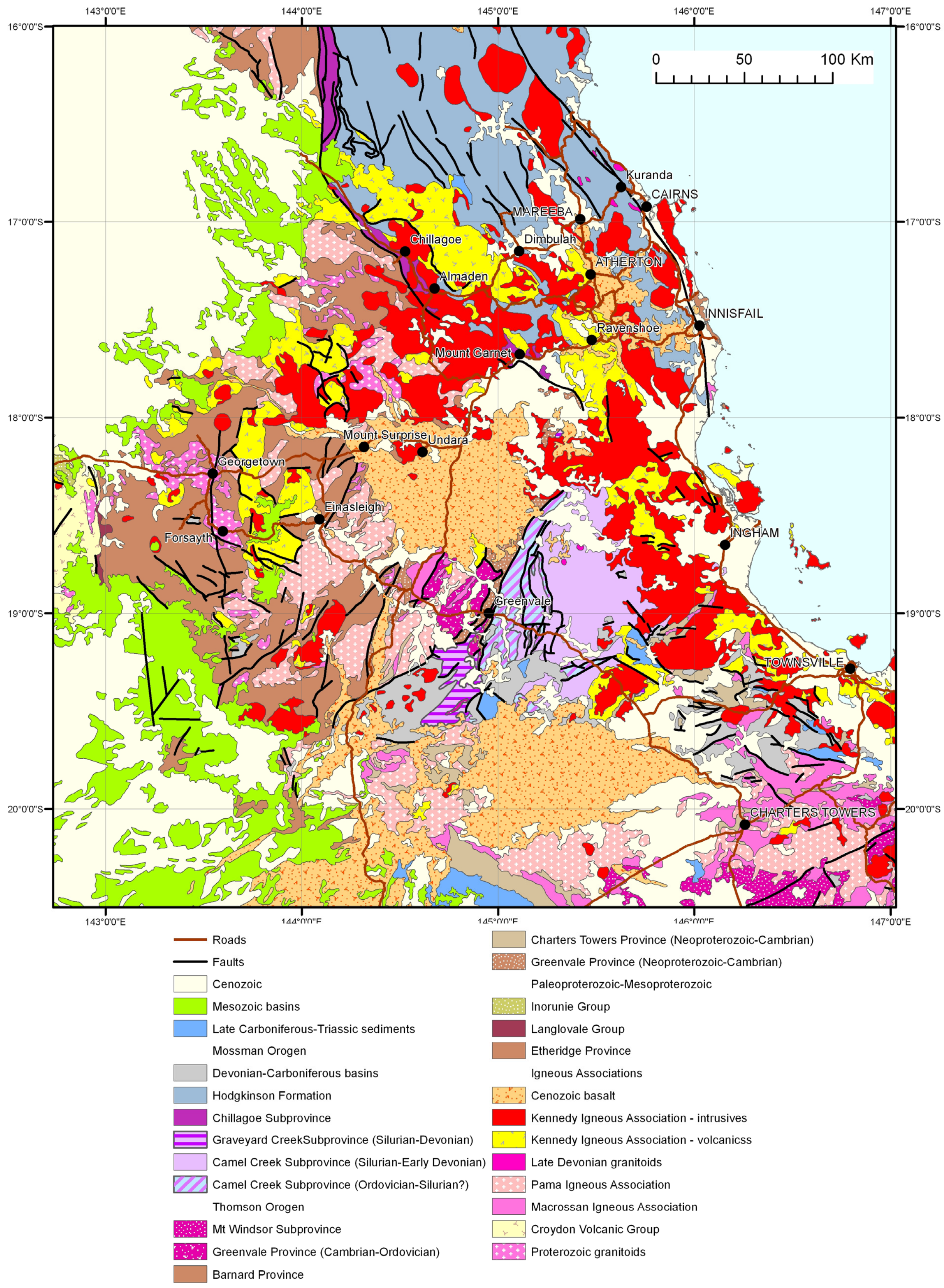


Figure 2. Generalised geology of the excursion route

Day One

Optional program

An optional afternoon trip after participants arrive in Cairns to examine some outcrops along the coast north of Cairns has been included here, but at the time of writing, it had not been confirmed that this will be possible.

Cairns to Ellis Beach

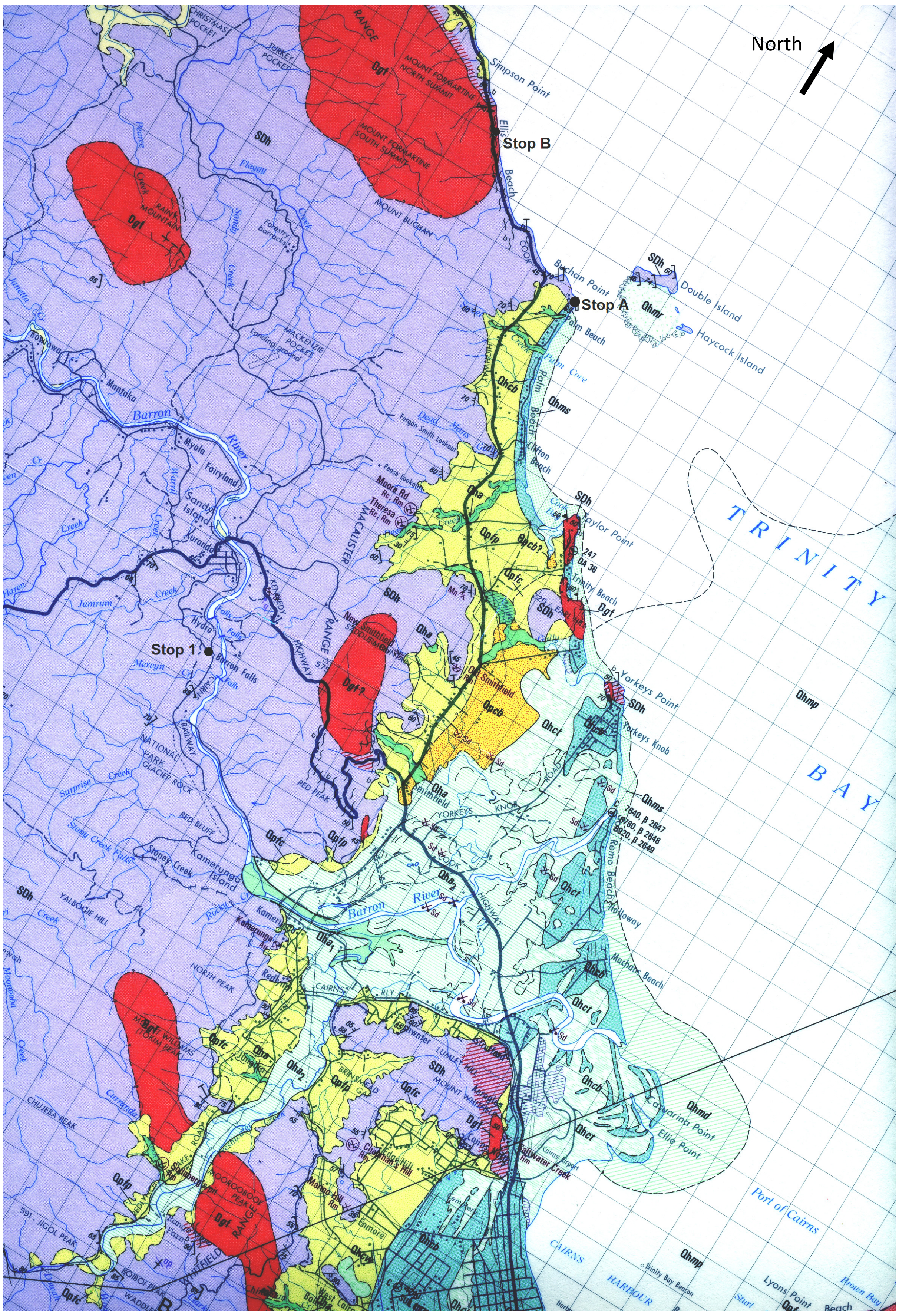
North of Cairns, the Captain Cook Highway runs close to the Macalister Range consisting of Devonian Hodgkinson Formation intruded by plutons of Mount Formartine Granite. The assemblage is poly-deformed, with shortening strain imposed in both the earliest Carboniferous and Permian. The coastal plain is covered by alluvial/colluvial and paludal Quaternary deposits. Dates from the application of OSL, TL and radiocarbon techniques show that coarse fanglomerates from elevated coastal terraces date back to 81 ka, with a period of vertical alluvial accretion of up to 15 m of sediment between ~28 and 15 ka, after which Holocene dissection prevailed (Thomas & others, 2007). Cairns city itself is largely built on an assemblage of chenier dunes emplaced during cyclonic events. Trinity Inlet represents a former mouth of the Mulgrave River which shifted course to a more southern location.

Stop A: Palm Cove. UTM 55K 358350 8148900. Figure 3

The headland at the north end of Palm Cove exposes steeply dipping to subvertical, highly strained mélange. A protolith of quartzose to sub-labile sandstone, siltstone and mudstone has been extensively disrupted (D_1) to form block-in-matrix mélange at a range of scales. The original mélange fabrics have been modified by overprinting shear strain to produce a pervasive fabric coplanar with mélange phacoid orientation and the relicts of bedding. From regional structural analysis, including very extensive microstructural studies, this represents a composite S_2/S_4 fabric which is ubiquitous in the eastern and central parts of the Hodgkinson Province (Davis & others, 2002) and induced by regional compression which occurred in discrete late Devonian and Permian orogenic episodes (Davis & Henderson 1999). The generation of quartz veins in the Palm Cove exposure overlapped with compressive strain because some are folded. The sporadic incorporation of vein quartz as pods in the mélange implies that it had an involved history with late-stage reactivation. Locally phacoids show down-dip elongation and both dextral and sinistral shear sense asymmetries are represented.

Stop B: Ellis Beach. UTM 55K 354850 8151250. Figure 3

Several discrete bodies of Mount Formartine Granite have been mapped near Ellis Beach and in the Macalister Range. Although somewhat zonal, foliation is extensively developed and is coplanar with that developed in country rock of the Hodgkinson Formation. The outcrop to be examined is typical. Microstructural studies by Zucchetto & others (1997) have shown fabric to be a composite of D_2 and D_4, with subhorizontal S_2 also in evidence. Intrusion of the granite close to the Devonian–Carboniferous boundary at 357 ± 6 Ma (based on U-Pb SHRIMP zircon dating by Zucchetto & others) is considered to have occurred during D_2. A stock of mineralogically and geochemically distinct and unfoliated Wangetti Granite occurs 10 km to the north at Wangetti Beach amongst Mount Formartine Granite plutons. Whole rock Rb–Sr dating of the Wangetti Granite at 285–273 Ma places it as early Permian with younger K–Ar biotite ages of 255–235 Ma recording post-D_4 uplift and cooling. A similar K–Ar age of 247 Ma has been obtained for Mount Formartine Granite at nearby Trinity Beach.


North
Stop B
Stop A
Stop 1
TRINITY BAY
Double Island
Haycock Island
Port of Cairns

Day Two

Leaving Cairns, the route follows the Captain Cook Highway (Highway 1) north for about 12 km to the suburb of Smithfield, where the Cairns campus of James Cook University is located. The route follows the narrow coastal plain, dominated by Quaternary sediments and bounded on the west by the steep coastal scarp that forms the eastern edge of the Atherton Tableland. Elevations range up to approximately 800 m. The oblique orientation of the highlands relative to the prevailing south easterlies results in a tropical wet climate for Cairns, compared to the wet/dry monsoonal climate of much of tropical Australia. A lush tropical rainforest covers the steep slopes of the escarpment and the hinterland plateau.

The main drainage features are:

- the Barron River, which rises on the Atherton Tableland and enters the coastal plain through the spectacular Barron Gorge;
- Freshwater Creek, which joins the Barron River below the Gorge and drains the Lamb and Whitfield Ranges. It is dammed at Copperload Falls to create Lake Morris — the main storage for the Cairns water supply;
- the network of small creeks that flow into Trinity Inlet.

Bedrock in the Cairns region consists of folded and cleaved metamorphosed Devonian sediments of the Hodgkinson Formation and early Mississippian and Permian granite bodies, which form most of the higher altitude upland. The prominent coastal escarpments of the Cairns region rise to the Great Dividing Range, a large-scale physiographic feature of eastern Australia which separates westerly and easterly directed drainage. For the Cairns region, the position of the Great Dividing Range is considered to have had enduring stability based on the distribution of relict alluvial deposits (Forsayth & Nott 2003). Erosion has occurred most rapidly in the metamorphosed sediments, leaving granite plutons as isolated hills and ranges east of the main escarpment.

At Smithfield, the route veers left and takes the Kennedy Highway towards Mareeba and begins to climb the escarpment through tropical rain forest. Cuttings along the road expose cleaved metasedimentary rocks of the Hodgkinson Formation.

Stop 1: Barron Falls (Figures 3 and 4)

About 30 km from Cairns, we will turn left off the highway through Kuranda to Barron Falls (about 6 km), where the Barron River flows over the edge of the escarpment in a spectacular water fall at times of substantial drainage discharge.The river has incised the escarpment to form a prominent, narrow gorge below the falls. Capture of some of the tributaries of the west-flowing Mitchell River, may have strengthened the Barron River, causing it to cut back into its valley, producing the steep, narrow Barron Gorge below the falls. The falls are relatively placid at this time of year, the height of the dry season, and much of the flow of the Barron River is held back by the Tinaroo Dam and diverted into irrigation channels. In the wet season, the vista is often entirely different.

The rocks exposed in the walls of the gorge are largely cleaved low-grade pelitic metasediments. The rocks show evidence of multiple deformations ranging from Late Devonian to Permian. The apparently more complex deformation in the rocks in the Cairns area compared with those to the west led earlier workers (e.g. de Keyser & Lucas, 1969) to suppose that these rocks were potentially older and they were assigned to the Barron River Metamorphics. More recent work has shown that the rocks pass imperceptibly westwards into the Hodgkinson Formation. The rocks are affected by the Permian Hunter–Bowen Orogeny which in north Queensland is restricted to a narrow belt along the coast.

Figure 3 (opposite): Geology of the Cairns – Kuranda area. Quaternary units are: Qha –alluvium; Qhcw – swamp deposits; Qhct – estuarine deposits; Qhcb – beach ridges and cheniers; Qhms – shoreface and intertidal deposits; Qhmd – deltaic sand; Qhmp – prodelta deposits; Qhmr – reef rock and detritus; Qpfp – alluvial fans; Paleozoic units are SDh – Hodgkinson Formation; Dgt – Mount Formartine Granite. From Cairns 1:100 000 Special Geological Sheet. Grid squares are 1 km.

Figure 4: Barron River Falls

We now return to the Kennedy Highway and continue towards Mareeba. Some cuttings along the highway show weathered exposures of bedded sedimentary rocks, typical of the Hodgkinson Formation, but safety considerations on this busy road will preclude us from stopping.

Kuranda – Dimbulah – Thornborough

The country rapidly becomes drier west of Kuranda and the rainforest gives way to savannah woodland. This area is the northern part of the Atherton Tableland and the country is used mainly for cattle grazing and agriculture.

We will leave the Kennedy Highway and drive through Mareeba towards Dimbulah. Mareeba was settled in 1877 by John Atherton, after whom the tablelands are named. Traditionally an agricultural area, the rich red soil derived from Pliocene to Pleistocene basalt was once known mainly for tobacco until the crop was deregulated in 1995. By 2002 the crop had disappeared from the region but the distinctive tobacco drying barns are still a common feature. Tobacco was replaced by a wide range of crops including navy beans, sugar, coffee, ti-trees, macadamias, avocados and numerous varieties of exotic tropical fruits.

Outcrop of the Hodgkinson Formation is limited along this section and is mostly obscured by Cainozoic colluvium and alluvium of the Barron and Walsh River valleys. Whaleback outcrops of Mareeba Granite are exposed about 10 km south-west of Mareeba on the edge of a low escarpment which marks the main drainage divide (Great Dividing Range). The granite contains both muscovite and biotite and is classed as an S-type.

Several large ridges are passed on the route to Dimbulah. These are formed by the Hodgkinson Formation, but are buttressed by swarms of felsic dykes of Carboniferous to Permian age. The Permian Walsh Bluff Volcanics are visible as a range to the south. All of these igneous rocks are part of the Kennedy Igneous Association.

Because the Hodgkinson Formation is not well exposed along the main road, it is planned to examine the rocks to the north in the Thornborough area. The formation is very extensive in distribution, extending from the coast westward for some 150 km with its meridional extent exceeding 300 km. It consists of sandstone and mudstone in variable proportions, commonly as Bouma sequences, with a minor contribution of redeposited conglomerate, basalt and chert and rare limestone lenses (Bultitude & others, 1997; Withnall & Henderson, 2012). Deposition is considered to relate to gravity flows building deep sea fans. Bedding attitudes are steep. Rare fossils are mostly lycopod fragments and corals and conodonts from limestone clasts. As a consequence it is poorly dated but considered to be late Silurian to Late Devonian (Fammenian).

In the township of Dimbulah, we turn right onto the Dimbulah–Wolfram road for about 2 km across the Walsh River, then turn right onto the Thornborough Road and follow that north-north-west for about 33 km to the site of the former township of Thornborough at the crossing of the Hodgkinson River. The topography becomes progressively more rugged and dissected away from the Walsh River, and this is typical of most of the Hodgkinson Basin.

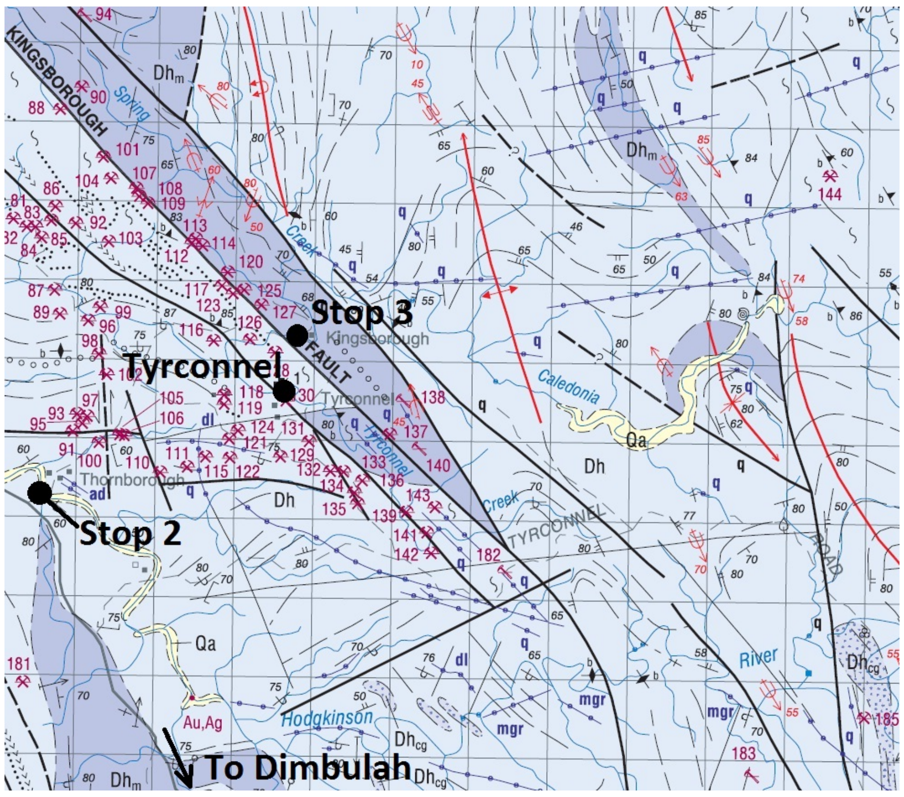


Figure 5: Geology of the Tyrconnel area: Qa – Quaternary alluvium; Dh - Hodgkinson Formation (sandstone and mudstone in subequal proportions); Dh_m mudstone with subordinate sandstone; Dh_{cg} - conglomerate lenses. From Rumula 1:100 000 Geological Sheet. Grid squares are 1 km.

Stop 2: Hodgkinson River crossing near Thornborough townsite, UTM 55K 287700 8125500, Figures 5 and 6

Outcrops downstream of the crossing consist of very thick-bedded, coarse- to very coarse-grained, very poorly sorted, locally pebbly litho-feldspathic sandstone, typical of the sandy facies of the Hodgkinson Formation (Figure 6). The pebbles consist of quartz and reworked sediments including shale, siltstone and chert. Volcanic fragments are noticeably absent, a feature common throughout the Hodgkinson Formation and raised as an argument against the Hodgkinson Basin being an accretionary wedge in a forearc position in a subduction related setting. The dominance of quartz, feldspar and the presence of detrital mica indicate that the provenance was largely cratonic. Age spectra for detrital zircon are known for six samples of the Hodgkinson Formation. One of these, obtained from west of Stop 4, is consistent with a cratonic source but the others from more easterly locations across the province show a significant to dominant Paleozoic contribution.

Bedding is poorly defined by the pebbly stringers, but appears to be steep (east) to vertical here and cut by a fracture cleavage dipping moderately to the west.

Stop 3: Creek crossing near Kingsborough, UTM 55K 290800 8127420 (Figures 5 and 7)

We continue along the road past the Tyrconnel mine for another 5.5 km. An exposure on the bank of the creek just downstream of the crossing displays a typical example of mélange that occurs through the Hodgkinson Formation. The rocks were originally thin- to medium-bedded turbidites consisting of alternating fine- to medium-bedded quartzo-feldspathic sandstone and mudstone. Here the sandstone beds have been strongly disrupted, forming phacoids up to 50cm long in a matrix of strongly cleaved mudstone (Figure 7). The anastomosing cleavage dips steeply to the east and in places appears to be slightly oblique to the phacoids.

At regional scale, four sequential deformation events are recognised for the Hodgkinson Formation (Davis & Henderson 1999). D_1 is a variably developed, weak bedding-parallel fabric and also widely expressed as mélange development. Proponents of a subduction complex model for the Hodgkinson Formation consider this deformation to be a consequence of imbrication induced by offscraping. D_2 represents E–W contraction across the Hodgkinson Province and the imposition of thrusting and slaty cleavage folding. SHRIMP U–Pb dating of zircon from syn-deformational granite bodies places its inception at the Devonian–Carboniferous boundary (Zucchetto & others, 1999). D_3 was an extensional episode which locally produced recumbent folds and associated cleavage. Relationships to dated granitoid bodies place it as early Permian. D_4 reflects renewed compression with its stress field almost identical to that of D_2. In some areas, D_2 and D_4 fabrics are discrete but for most of the region they are coaxial and inseparable. The age of syntectonic granitoids, and those registering D_4 fabric development, place this deformation as spanning much of the Permian (285–250 Ma). It registers the Hunter–Bowen Orogeny which is general for eastern Australia.

In the western part of the Hodgkinson Formation, its strata are thought to be disposed in a series of stacked upturned slices, within which younging directions are mainly to the west. The slices are bounded by thrust planes which in some areas are represented by zones of D_1 mélange.

For the Tyrconnel area, D_1 is expressed mainly by mélange. D_2 produced the main structural features expressed as widespread, open to tight N–S-trending folds that have vertical axial planes, moderate to vertical plunges and are visible both on air photographs and at outcrop scale. A weak to strong axial plane cleavage, S_2, is associated with the folds over much of the area. Following D_2 zones of heterogeneous north-west-trending shearing were initiated. These appear to have reactivated some pre-existing (D_1) thrusts which bound sedimentary packages (for example the nearby Kingsborough Fault). It is most intense along such faults but also forms many anastomosing zones of high strain, often expressed as mélange or internal disruption and transposition of bedding. Some of these zones are mylonitic with moderately plunging stretching lineations indicating some transcurrent as well as vertical movement.

Figure 6 (above): Pebbly sandstone of the Hodgkinson Formation at Stop 2

Figure 7 (right): Strongly boudinaged sandstone beds in a cleaved mudstone matrix in the Hodgkinson Formation at Stop 3

In this area, there are three main mélange zones; these lie along the Kingsborough Fault (the "Central Mélange Zone" of Peters, 1987), the Monarch Fault, and between the Hodgkinson River and Pennyweight Creek. There is no obvious difference between the lithologies in the zones and in the surrounding country except for their degree of deformation. The shear zones generally trend north-north-west and the associated cleavage dips 60° to 90° to the east. Lineations are quite weak, but the pitch of phacoid-elongation ranges most commonly from 50° to 90° north-east, in the plane of shear.

The outcrop at this site lies within the Central Mélange Zone for which Peters (1987) deduced a dextral shear sense in plan, with a substantial vertical component displacing the north-east side down. Lithological offsets noted by Peters (1987) suggest a displacement of 100 to 300 m along the shear.

Davis & others (1998) identified an anomalous zone (the Desailly Structure) for the central Hodgkinson Province some 20 km wide and trending NE-SW, marked by diffuse brittle structures and an alignment of granitoid bodies. It was considered to be syn- or post D_2 in generation with reactivation in D_4.

Lunch stop: Tyrconnel mine, UTM 55K 290750 8126550

The Hodgkinson gold field discovered by Venture Mulligan in 1875 was a reef field rather than alluvial like the more famous Palmerville gold field. By 1878 the town of Thornborough had been gazetted, followed by Northcote and Kingsborough in 1880. The total European population in 1878 was 1082, with about 1900 Chinese. Thornborough had at least 12 hotels. The field became infamous as a result of a battle between European and Chinese miners, sparked by a rash of claim jumping. On 9 January 1880 a clash between a digger and some claim jumpers escalated into a pitched battle that left 5 diggers dead and 12 wounded, and at least 57 Chinese dead. The Chinese fled the field.

The reefs, although rich, were developed haphazardly and poorly and most miners and machines moved on to other fields, beginning with an exodus to the tin fields of Herberton in 1880. The population of Thornborough had dropped to 50 by 1886.

Up to 1877, at least 3.11 tonnes of gold was recovered from alluvial and reef deposits. The principal mines were the Tyrconnel, General Grant and the Flying Pig Group, of which the latter was the major producer. Most work stopped at the water table. Peak annual production was 1.257 tonnes of gold in 1878, at an average ore grade of 59 g/t gold. Despite head grades above 30 g/t, production declined from 1880 as a result of high costs due to isolation. In an effort to conserve money, miners used primitive mining methods (mostly hand shovelling and winding) and scant timbering. By 1882, there were only four mines worked by steam machinery and nine with horse-drawn whips or whims. Expensive milling machinery had been brought in but the mill owners charged fees to recoup the investment and running costs. Total gold production up to 1886 was approximately 5.40 tonnes. The advent of company mining in the early 1890s was a dismal failure. The first and longest-lasting of these companies was the Tyrconnel Gold Mining Company, which was formed to work the Tyrconnel and Lizzie Redmond lines of reef. The Tyrconnel was sunk to 131 m, the deepest mine on the field in 1884. For five years, during the depression of the 1890s, the field was virtually deserted.

Mining at deeper levels was undertaken at the turn of the century with the advent of cyanidation, and an injection of company funds was focussed on the General Grant mine, which was deepened to 176.8 m. The Hodgkinson United Gold Mining Company deepened the Tyrconnel mine to a record 224 m down-dip depth. High mining costs again forced closure of the mines. The larger mines were rehabilitated in the 1930s and early 1940s, during which time development work was undertaken to find additional reserves. These mines closed in the early 1940s as a result of poor profitability.

Figure 8: Boilers at the Tyrconnel mine

The Tyrconnel mine reopened in 1982 and the battery was refurbished to treat dump material, which yielded more than 24.3 kg of gold bullion. Intermittent small-scale mining continued until 1985 when exploration intensified. From 1987 to 1989 Gold Copper Exploration Ltd developed an opencut mine along the Lizzie Redmond reef and drove a decline down to Level 3 in the Tyrconnel mine. Dump material from various mines was screened and, together with mined ore, was treated at their Sunnymount plant, 83 km to the south-east of Thornborough. This operation yielded 297.7 kg of bullion containing 117.5 kg of gold and 135.5 kg of silver. The average grade of the treated ore was 3 g/t Au. All operations ceased in 1989 when the company went into liquidation. The Tyrconnel mine was sold to the Bell family which restored the site for its historic value, and as a tourist attraction. Mine tours include a demonstration of the historic stamper battery at work.

Mineralisation consists of gold–quartz and gold–stibnite quartz veins hosted by the Hodgkinson Formation. The quartz veins range from a few centimetres to a maximum of 3 m wide and contain only minor sulphides. A marked coincidence of mine distribution with the dominant north-west trend of the major and minor faults in the region, indicates a structural control either parallel or trending at a low angle to these regional shear zones. Most lodes are steeply dipping and cut across the bedding and regional foliation. The veins are a complex mixture of gouge and inclusion-rich quartz. The quartz is massive, milky-white and deformed, with abundant laminations, stylolites and clear quartz veinlets. The veins show evidence of incremental quartz deposition. 'Ribbons' or laminations of dark grey country rock and associated sulphides within the quartz are commonly associated with higher gold grades, and may be concentrated on one side of the reef. The laminations are thought to have formed from a crack-seal process. Other gold-bearing vein types include massive (buck) quartz, complexly brecciated quartz, and fractured quartz. A footwall quartz-stringer zone is also present in many of the workings. Minor sulphides associated with the gold include galena, arsenopyrite, pyrite, sphalerite, chalcopyrite and stibnite. Poorly developed sericitic and argillic alteration zones form selvedges, a few centimetres wide, adjacent to the veins.

The gold–quartz and gold–stibnite quartz veins are confined to discrete structural zones where they are localised in shears and secondary brittle reactivation zones along axial planes of folds. These discontinuities are associated with larger, commonly regionally significant shear and mélange zones, which show multiple deformations. The gold mineralisation in the Hodgkinson Gold Field, for example, is associated with the Retina, Monarch and Kingsborough Faults (central mélange zone).

Studies of the structural, paragenetic, stable isotopic and fluid inclusion characteristics of the gold and gold–stibnite veins support a model involving a post-tectonic mineralising event for the formation of these ores. Fluid inclusion studies by Peters (1987) indicate no evidence of boiling and suggest mesothermal temperatures of 285–335°C.

Phillips & Powell (1992) proposed a metamorphic model for the formation of gold-only deposits similar to the Hodgkinson Gold Field. Their model has the gold scavenged from the country rocks by low salinity, high temperature (>200°C) reducing fluids derived from devolatilisation during regional metamorphism. These fluids are enriched in sulphur (due to the presence of pyrite in the host rocks) and form ideal gold transporters in a Au–S complex. The deposition of the gold is considered to occur at temperatures of between 250°C and 400°C and can be due to interaction with Fe-rich country rock, a drop in temperature, or lower oxygen activity. The distribution of the fluids is controlled by major shear zones.

A complex apparent age spectrum obtained from sericite associated with gold mineralisation of the Minnie Moxham deposit of the Hodgkinson gold field obtained by Vos & others (2007), was interpreted as indicating a ~340 Ma age for mineralisation. It is likely to express a cooling age following D_2 deformation of the Hodgkinson Province. Elsewhere in the province there is evidence of gold mineralisation associated with the Permian D_4 Hunter–Bowen orogenic episode (Davis & others, 2002).

Dimbulah to Almaden

After lunch, we return to Dimbulah and drive towards Chillagoe along the Burke Developmental road. About 8 km south-west of Dimbulah, the road begins to pass through hillier terrain formed by various units of the late Carboniferous to Permian Featherbed Volcanic Group, which were emplaced largely within a composite volcano-tectonic subsidence structure about 100 km long and 30 km wide — the Featherbed Cauldron Complex (Mackenzie, 1993; Bultitude & others, 1997).

The Featherbed Cauldron Complex is the largest of a number of these structures in north Queensland, which are all part of the Kennedy Igneous Association.

This structure consists of nine overlapping collapse structures. Most are 'classic' ring fault and ring dyke-bounded cauldron collapse structures, although the Boonmoo Sag at the south-eastern end of the complex is a basin-like sag structure without peripheral ring fault(s) or ring dykes. Each cauldron contains, or is adjacent to, a unique sequence of eruptive rocks.

Total preserved volume of eruptive rocks in and around the cauldron complex is about 3000 km^2, and it is estimated that between 500 m (Featherbed Cauldron) and at least 1 km (Boonmoo Cauldron) of material have been removed by erosion. About 85% by volume of the Featherbed Volcanic Group is welded rhyolitic ignimbrite, and about 10% is dacitic to andesitic ignimbrite. The remaining 5% consists of: dacitic to andesitic lavas; rhyolitic lava flows and domes; rare unwelded pyroclastic rocks including tuffs; and very rare reworked (sedimentary) volcaniclastic rocks.

Stop 4: Burke Developmental Road, UTM 55K 284150 8083850, Figure 9

The Muirson Rhyolite is the basal unit within the Boonmoo Volcanic Subgroup of the Featherbed Volcanic Group and is well exposed on a westward-facing scarp at this locality.

Although the rhyolite is well exposed in a large road cutting, outcrops on the adjacent hillside on the southern side of the road are equally as informative and safer points for a large group to examine the rocks. In any case, wear your visibility vest.

The rocks consist of green very crystal-rich, lithic poor rhyolitic ignimbrite. The crystal fragments consist of beta-quartz to 5mm and pink to cream feldspar. Mafic mineral clasts are less common, but include biotite and hornblende. Fiamme up to 10cm long have been recorded in this unit, but are rare at this locality. The Muirson Rhyolite has not been dated, but a Rb-Sr total rock isochron age of 308±8 Ma has been obtained for the overlying Hopscotch Rhyolite.

Continuing west along the Burke Developmental Road, the low-lying country immediately to the west of the scarp is formed by the Retire Monzodiorite. This has a similar Rb-Sr age to the Boonmoo Volcanic Subgroup, whereas the hills to the north-west are one of the younger parts of the cauldron complex, the early Permian Wakara Volcanic Subgroup.

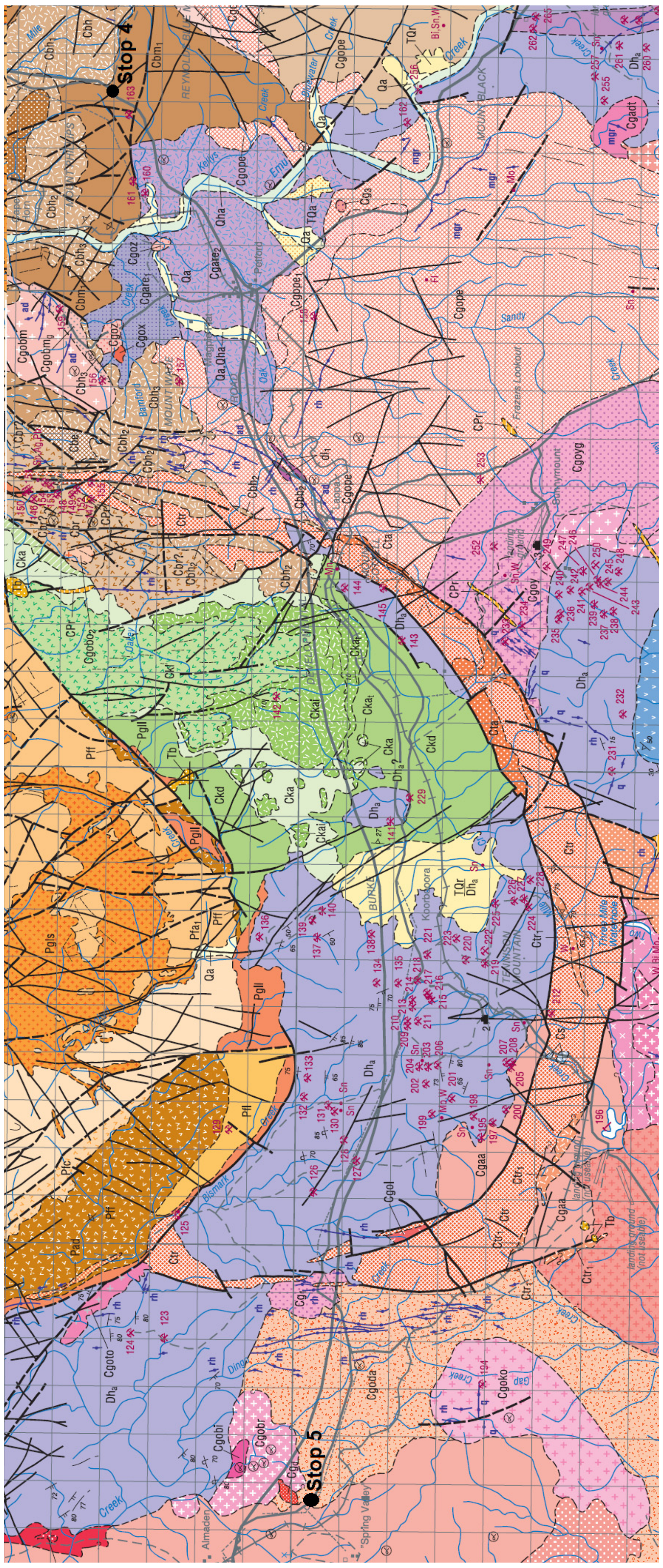


Figure 9: Geology along the Burke Developmental Road in the Petford area. Dh_3 – Hodgkinson Formation; units prefixed by Cb – Boonmoo Volcanic Subgroup (including Cbm_1 - Muirson Rhyolite); Ck – Tennyson Volcanic Subgroup; Cgo –Ootann Supersuite; Cga – Almaden Supersuite; Ctr – Tennyson Ring Dyke; Pf – Wakara Volcanic Subgroup.. From Chillagoe 1:100 000 Geological Sheet. Grid squares are 1 km.

After passing through the small settlement of Petford, the road traverses through slightly hillier country that is formed by the Petford Granite (Rb–Sr age of 305±6 Ma), a pink to grey, porphyritic hornblende-biotite granite.

About 9 km from Stop 4, and just west of the railway siding at Lappa, the road crosses a northerly-trending ridge formed by rhyolite of the Tennyson Ring Dyke, which bounds one of the cauldron collapse structures. The range of hills to the south is formed by the southern part of the ring. Within the eastern part of the cauldron, outcrop consists of rhyolitic ignimbrite units with variable amounts of lithic and crystal fragments (Tennyson Volcanic Subgroup). Hodgkinson Formation crops out in the western half of the cauldron and represents the floor of the structure.

Stop 5: Burke Developmental Road, east of Almaden township, UTM 55K 254550 8079650, Figure 9

This is the last official stop of the day. The David Granite is exposed here as large outcrops north of the road, with multiple blasted boulders on the south side for inspection. This unit has an approximate 301 Ma Rb-Sr age and belongs to the Ootann Supersuite, one of three voluminous Carboniferous to Permian granite supersuites in the local area. It is representative of the Kennedy Igneous Association. In the Almaden–Ootann area, these intrude through, and hence mask, the Palmerville Fault — the major crustal break in this area.

The outcrop consists of white-pink, sparsely enclave-bearing, seriate, medium- to coarse-grained (mostly <1cm, up to 1–2cm), biotite monzogranite. Dominant minerals are quartz, K-feldspar and plagioclase, with lesser biotite (~6%). The granite contains grey, mostly rounded but also irregular-cuspate, equigranular to sparsely porphyritic, biotite-plagioclase enclaves, up to 5–15cm, with a microdioritic texture, and also minor thin biotite aplite veins.

This stop is on a main road so we need to be careful — wear your vest. Remember to look both ways — cars drive on the left hand side of the road in Australia.

Almaden – Chillagoe

The route to the overnight stop of Chillagoe traverses along outcrop of the Silurian to Early Devonian Chillagoe Formation (Figure 10). Outcrops of limestone and ridges of chert will be obvious along the route, but tholeiitic basalt and siliciclastic sedimentary rocks are also present. The rocks have been interpreted to have formed on a rifted continental margin in a range of environments from deep water to unstable carbonate ramps (Bultitude & others, 1997). In places the limestone bodies are interpreted as allochthonous blocks enclosed in deeper water sediments. The geology is complicated by repetition of units by numerous thrusts. We will visit the remains of the historic Chillagoe smelters if we arrive in Chillagoe before sundown.

Chillagoe was settled as a pastoral property by William Atherton in the late 1880s, and soon after deposits of copper, silver, lead, mica and some gold were found in surrounding areas. At first, small blast furnaces were used at mine sites in the surrounding area — Muldiva, Calcifer and Mungana — to process the ore. Heavy machinery and supplies were transported by horse-drawn wagons from Port Douglas on the coast, but the rough terrain and distance made large-scale ore treatment impractical.

In the late 1890s, the railway was extended from Mareeba, and by 1901 Chillagoe had become a flourishing town. The railway enabled equipment for the large, innovative Chillagoe Smelters to become operative by September 1901. The Chillagoe Company equipped its work sites with the most up-to-date machinery and the surrounding mines were worked on a large scale. The mines, railway and smelter provided employment for up to 1000 workers. However, the costs of transporting both coke and ore over the vast distances made the operations unprofitable. The company never paid a dividend and the smelters soon closed. In 1909 a branch railway was built from Almaden through Mount Surprise and Einasleigh to Forsayth in the hope of tapping into new ore supplies. The Chillagoe smelters were reactivated, but flooding and fire damage closed operations in 1914.

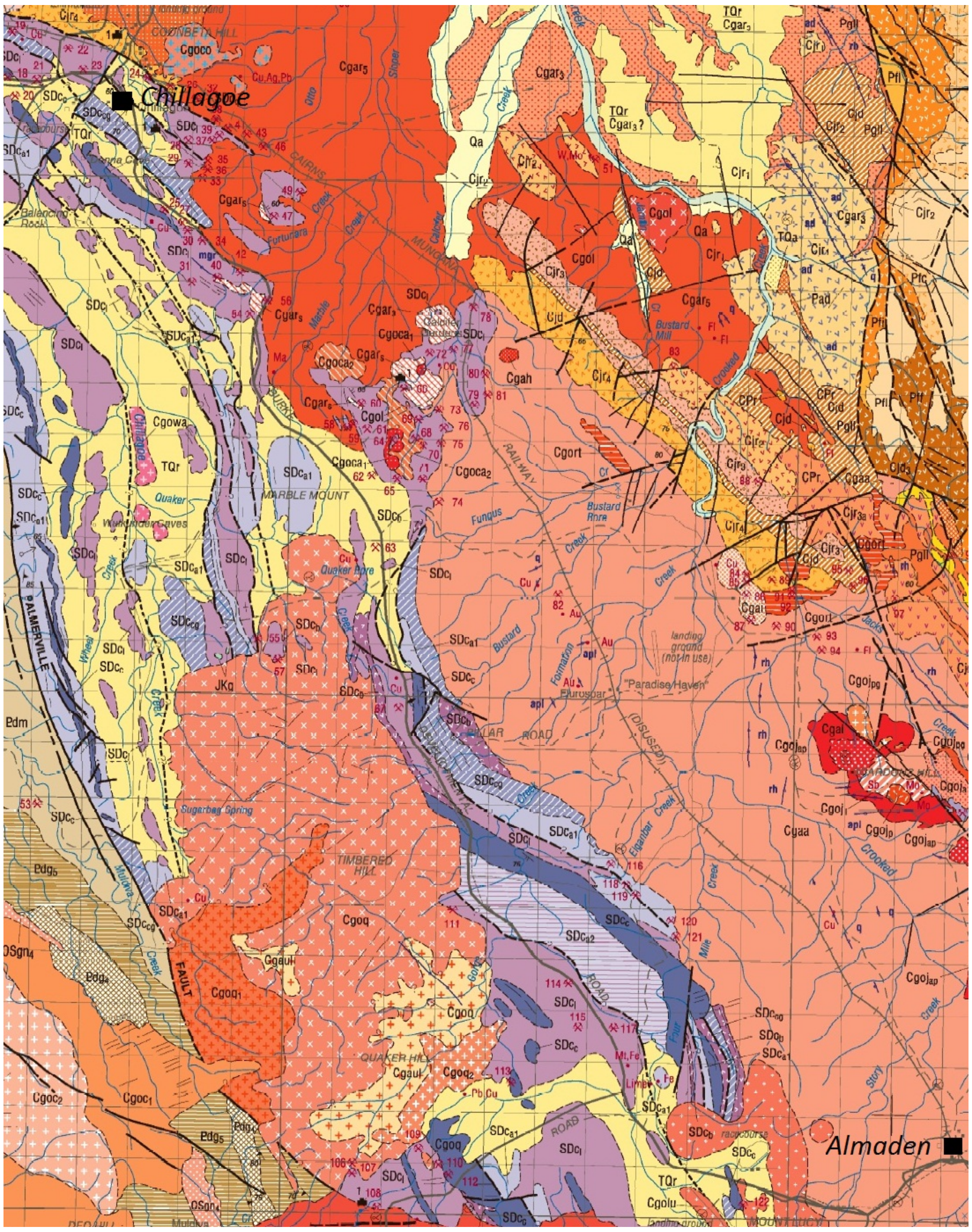


Figure 10: Geology along the Burke Developmental between Almaden and Chillagoe. Units to note are: those prefixed by SDc – Chillagoe Formation including SDc_l limestone, SDc_c chert, SDc_{cg} conglomerate, SDc_a sandstone-dominated, SDc_b basalt); Cgo –Ootann Supersuite; Cga – Almaden Supersuite; Pf – Featherbed Volcanic Group. Ꞓd – Dargalong Metamorphics. From Chillagoe 1:100 000 Geological Sheet. Grid squares are 1 km.

Figure 11: Remains of Chillagoe State Smelter

In 1919 ownership of the smelter was transferred to the Queensland Government. The smelter operated until 1943 and in its lifetime treated 1.25 million tons of ore, yielded 60 000 tons of copper, 50 000 tons of lead, 181 tons of silver and 5 tons of gold. By 1943 other smelters were built closer to the then major ore producing areas such as Mount Isa. Easy access to these areas outweighed the economic usefulness of the State-run Chillagoe Smelter. Today the site is managed by Queensland Parks and Wildlife Service.

Chillagoe is now a major cattle centre, as well as a tourist destination, but mining still plays an important part in the area.

The Mungana project, 15 km north-west of Chillagoe, was acquired by Kagara Zinc Limited in 2003. Kagara then committed to the development of the polymetallic deposit with decline access to the two main ore shoots commencing in 2006 with on-lode driving and stopping commencing in 2008. Ore from the Mungana operations was trucked to its central processing plant at Mount Garnet where it was blended with ore from Kagara's other mines. Kagara was actively exploring for other base-metal deposits along the Chillagoe belt, and had a number of promising projects, until experiencing financial difficulties and going into receivership earlier this year.

Mungana Goldmines was formed in early 2009 as a vehicle for Kagara's gold interests in the Chillagoe region, particularly at Mungana and Red Dome. The gold ore body at Mungana was defined over several years by Kagara, where it was developed as an adjunct to the base metal operations. The most recent resource estimate has defined an Inferred and Indicated Resource at a 0.35g/t AuEq cut-off of 32.2 million tonnes at 0.81 grams per tonne gold, 0.19% copper and 12g/t silver.

The Red Dome deposit is located 3 km south-east of the Mungana mine and is a porphyry-related gold-copper-silver-molybdenum deposit which was developed as an open pit mining operation by Elders Resources and Niugini Mining between 1986 and 1996, when over 1 million ounces of gold and 30 000 tonnes of copper were produced. Kagara acquired the Red Dome deposit from Niugini Mining in 2003 and commenced deep exploration drilling to define additional resources below and adjacent to the abandoned open pit. This work culminated in the 2009 resource estimate by Kagara at 0.35g/t AuEq cut-off of 40Mt @ 0.79 g/t Au, 0.3% Cu, which was identified below and as lateral extensions of the historical Red Dome open pit. The Mungana and Red Dome gold deposits have combined measured, indicated and inferred resources of 1.85 million ounces of gold, 180,000 tonnes of copper and 13 million ounces of silver.

Many small marble mines have been worked in the area, although it has been found that in spite of the very fine quality of the marble, it is not economically feasible to compete with overseas markets.

Day Three

Stop 6: Balancing Rock, 2.8 km south-west of Chillagoe, UTM 55K 235500 8099850, Figures 12 and 13)

Although containing a wide variety of sedimentary rock types and basalt, the Chillagoe Formation is typified by limestone. In general the limestone is lime mud, variably recrystallised to marble. Locally it is fossiliferous with corals and stromatoporoids as well as megalodont bivalves, which are commonly in growth position. These and conodonts indicate that the formation is Silurian – Early Devonian (Telychian – Emsian).

The Chillagoe area is noted for its spectacular landscape of jagged limestone towers and its extensive cave systems, many of which are protected within the Chillagoe-Mungana Caves National Park. The Royal Arch Cave is located about 5 km south-west of Chillagoe while the Donna, Pompeii, Bauhinia and Trezkinn caves are located 1.8 kilometres from the centre of town. Royal Arch, Donna and Trezkinn caves can be visited by guided tour only. Time will not permit us to visit these, but a short visit will be made to Balancing Rock.

From the car park, 2.8 km from Chillagoe, a rough track climbs up the rock formation to view the spectacular limestone tower karst and the surrounding landscape of open woodland. Balancing Rock is an isolated limestone pillar, and in addition the limestone shows many other features characteristic of karst, such as fluting (rillenkarren) and joints accentuated by solution (grikes).

The Wallumba Aboriginal art site near Balancing Rock has viewing access provided by a boardwalk.

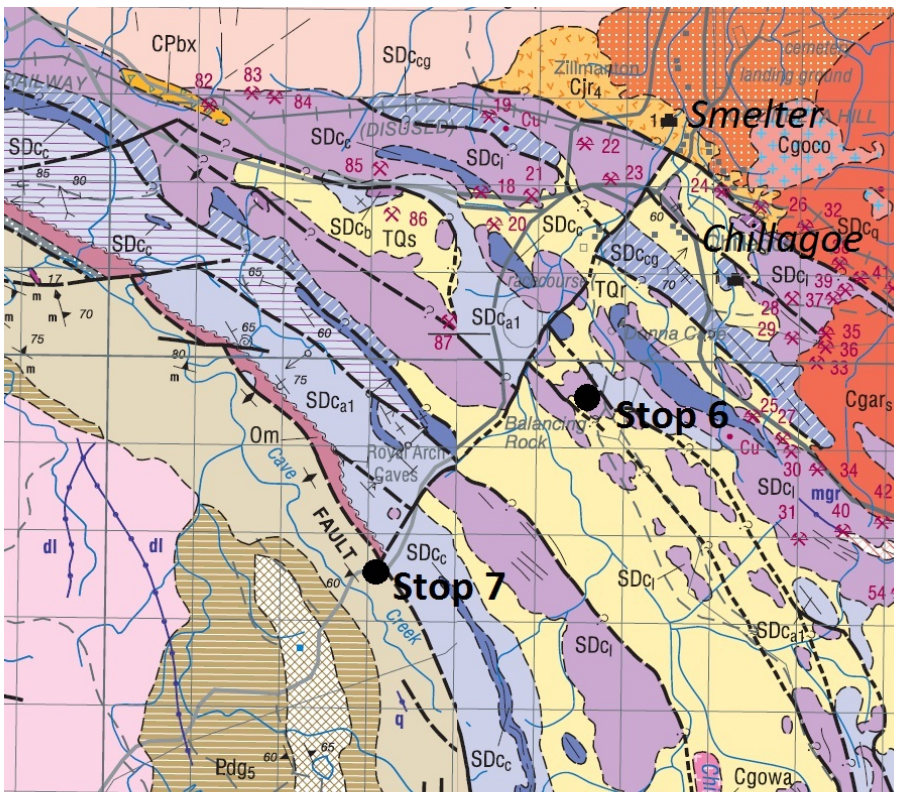


Figure 12: Geology of the Chillagoe area. Units to note are: those prefixed by Pd – Dargalong Metamorphics; Om – Mulgrave Formation; SDc – Chillagoe Formation including SDc_l limestone, SDc_c chert, SDc_{cg} conglomerate, SDc_a sandstone-dominated, SDc_b basalt); Cgo –Ootann Supersuite; Cga – Almaden Supersuite; Cjr – Redcap Volcanics. From Chillagoe and Mungana 1:100 000 Geological Sheets. Grid squares are 1 km.

Figure 13 (above). Typical karst features in the Balancing Rock National Park

Figure 14 (Left). Balancing Rock

Stop 7: Bolwarra Road, 5 km south-west of Chillagoe, UTM 55K 231890 8096130, Figure 12

The Palmerville Fault is crossed by the Bolwarra Road, about 5 km south-west of Chillagoe. Time will not permit detailed examination of the area, and the fault itself is not exposed. However, we will take a short drive along the road to the crossing of Cave Creek and point out where the fault is crossed.

After passing the turnoff to Royal Arch Cave, the road to Bolwarra passes through a series of ridges for about 400m. These are formed by relatively quartzose sandstone and pebble conglomeratic within the Chillagoe Formation. To the west of the ridge, the topography becomes more subdued, and this change is taken to mark the Palmerville Fault, which marks the so-called Tasman Line in this area.

West of the fault, the rocks are mapped as the Paleoproterozoic to Mesoproterozoic Dargalong Metamorphics which consist of porphyroclastic gneiss, augen gneiss, sillimanite-biotite gneiss and minor amphibolite. Siliceous mylonite with relict feldspar porphyroclasts locally occurs adjacent to the Palmerville Fault.

Chillagoe to Undara

We now return to Chillagoe and back-track to Mareeba and then south to Atherton. The route south of Mareeba will pass mainly over Pliocene Atherton Basalt. Hills to the west are of the Permian Walsh Bluff Volcanics. Views to the south-east are of the Bellenden Kerr Range, that includes Mount Bartle Frere, the highest point in Queensland at an elevation of 1622m. The range is formed from the early Permian I-type Bellenden Kerr Granite.

Much of the Atherton Tableland is formed by basalt and the outlines of several shield volcanoes have been identified. Activity began at about 7 Ma, but the most voluminous eruptions occurred between 4 and 1.2 Ma (Whitehead & others, 2007). Lava from these flowed over the coastal escarpment down the ancient Johnstone River almost to the current position of the coast near Mourilyan Harbour. Because of the high rainfall, the basalts have weathered deeply to the fertile red soils characteristic of the area and outcrops are limited.

At about 1 Ma, the style of eruptions changed to build up small scoria cones and 35 of these have been recognised. In the last 200 000 years pulses of basalt magma encountered groundwater and the resulting phreatic eruptions have resulted in the formation of maars, of which nine are identified. Palynological dating of sediments within the swamps and lakes that now fill them, suggest that they are between 23 000 and 9 000 years old. Aboriginal oral history tells a myth of the formation of Lakes Barrine, Eacham and Euramoo that are consistent with a volcanic eruption, placing the volcanism within times of human habitation of the area.

Just south of Atherton, we will pass a Pleistocene scoria cone (Figure 12). Rainforest originally covered much of the tablelands, but was cleared to make way for farming, in particular dairying. Remnant patches of rainforest remain and many of these are now National Parks. About 25 km from Atherton, we will come to Hypipamee, a small National Park in tropical rainforest.

Stop 8: Hypipamee Crater, near the Kennedy Highway, 28 km north of Ravenshoe, UTM 55K 339210 80726700, Figure 16

Depending on time, we will probably have lunch at Hypipamee. From the car park it is a 400m walk through tropical rainforest to a viewing platform at Hypipamee Crater, which is in an example of a diatreme. It is about 58m down to the water, which is 82m deep. The crater resembles a sinkhole in limestone terrain, but is in granite, belonging to the Carboniferous O'Briens Creek Supersuite. It is thought to have formed when basalt magma encountered groundwater, producing a phreatic eruption. There is little evidence of basalt, although some fragments have been found nearby in the past. Angular blocks of granite as large as refrigerators in the surrounding rainforest may have been blasted from the crater. The exact age is uncertain.

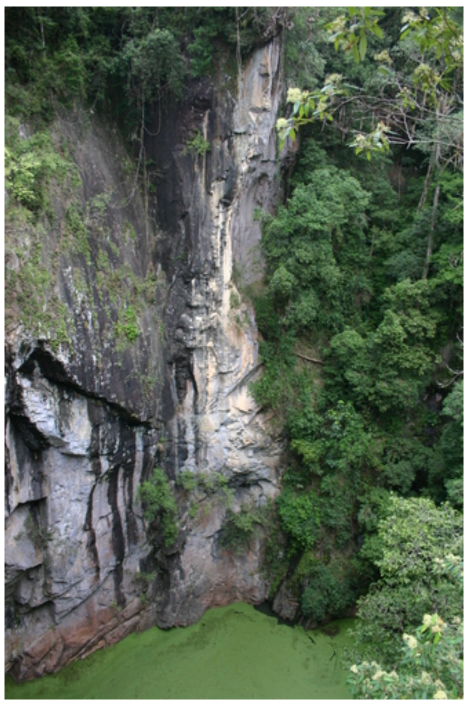


Figure 15 (above): Small cinder cone, about 5 km south of Atherton

Figure 16 (left): Vertical walls of Hypipamee Crater

After leaving Hypipamee we will travel south-west, and pass through Ravenshoe on the edge of the Atherton Tablelands. The annual rainfall decreases to the west and the vegetation progressively changes from rainforest to eucalypt forest and then into the open savannah style woodlands.

Stop 9: Innot Hot Springs, near the Kennedy Highway, 30 km west of Ravenshoe

We will make a brief stop at Innot Hot Springs, where water issues at a temperature of 74°C — the hottest measured natural spring water temperatures in Australia. The area was a favourite destination for early campers, who were attracted by claimed curative properties of the water and compared it with famous thermal spas in Europe. Up until 1914 the mineral water was bottled and sent to Europe to be used for medicinal purposes — mules hauled the water over the Cardwell Range to Townsville for bottling at the Innot Cordial Factory. The hot springs are still commercially operated as a tourist attraction. The source of the heat is uncertain, although many of the Carboniferous granites in the region have high background values of K, U and Th and are potentially heat-producing.

A Geothermal Exploration Permit (EPG29) in the area immediately surrounding Innot Hot Springs was granted in 2010 to Gradient Energy Limited. The geothermal project covers an area of 596 km^2 and is suitably located for future power supply into the main east coast grid. It differs from the hot fractured rock deep-drilling geothermal projects in that there is a known geothermal spring system expressed at the surface. Temperatures in the range 144°C to 165°C are predicted at depth, meaning that off the shelf geothermal power plant technologies could be used.

Continuing on from Innot Hot Springs we pass through Mount Garnet, which has had a long history of mining, once being the centre of a thriving tin mining industry. Tin was sourced from both hard-rock and alluvial sources. Nettle Creek east of the town was the site of a large dredging operation up until the mid-1970s. Zinc was mined by Kagara Zinc at the Mount Garnet mine, and the plant then served as a central milling operation for Kagara's mines as far afield as Chillagoe and Balcooma, until the company went into receivership. Concentrate was trucked to the Sun Metals Townsville Zinc refinery.

We continue along the Kennedy Highway towards Mount Surprise. Part of the route follows the line of the Great Dividing Range and outcrop is almost non-existent. The area forms part of an old land surface that has been extensively lateritised and covered by residual sand and clay. Sporadic outcrop and geophysical evidence (airborne magnetic data) indicates that the laterite is developed on granites of the Carboniferous Tate Batholith.

About 68 km from the Mount Garnet, we turn to the right onto the Gulf Developmental Road towards Mount Surprise and continue for another 17 km to the Undara turnoff. Outcrop consists of fresh basalt of the McBride Basalt Province, one of the major Pliocene to Recent lava fields of north Queensland.

The McBride Basalt Province was studied by Griffin & McDougall (1975) and Stephenson & Griffin (1976), who recognised 164 volcanic centres, including remnant plugs as well as lava and cinder cones and craters. The province is a large basaltic dome about 80 km across and nearly 500 m thick. The oldest rocks of the group are undifferentiated basalts which comprise more than half of the province and have ages between 2.7 and 0.5 Ma. Younger Quaternary flows can be mapped out on the basis of their surface morphology (Figure 17). The most extensive unit, the **Undara Basalt**, covers 1550 km^2 and is dated by K–Ar at 190 000 years. It hosts the area's famous lava tubes. Lava from the Undara Crater flowed 160 km down the ancestral Elizabeth Creek into the Einasleigh River, and another flow 90 km long entered the Lynd River in the Atherton Sheet area. The youngest lavas are the **Kinrara Basalt** for which an apparent K–Ar age of 70 000 to 50 000 years was regarded as a maximum by Griffin & McDougall (1975). Basaltic rocks in the McBride Province are predominantly nepheline-normative and include nephelinite, basanite, hawaiite, and mugearite.

The volume of lava erupted from Undara Crater is estimated at 23 km^3 (Atkinson & Atkinson, 1995). Most of the lava was the fluid *pahoehoe* type. Some of the lava found its way into old watercourses, mainly to the north and north-west, and thus channelled, the lava hardened on the top and sides to form insulated tubes which allowed it to flow long distances including 160 km to the north-west, reputed to be the world's longest lava flow from a single volcano.

Optional Stop 10a: Kilkani Cone: Undara National Park, UTM 55K 253350 7983620

If there is time this afternoon, we may visit Kalkani Cone, an impressive scoria cone that forms part of the Undara National Park. To reach it, we travel 6 km along the road to Undara Lodge, turn left at the fork and travel 6 km to the Kilkani day-use area. A track runs around the lip of the crater but there will probably not be time to complete this. Numerous examples of volcanic bombs and agglutinated spatter can be seen along the track.

The Undara Lava Lodge is about 14 km from the turnoff. The lodge has been in operation since 1990, running tours to the lava tubes and accommodating guests in a unique atmosphere. The guides are members of the Savannah Guides organisation, a network of professional guides with an in-depth collective knowledge of the natural and cultural assets of the tropical savannahs of northern Australia.

Unfortunately we were unable to secure accommodation at the lodge so our overnight accommodation will be in Mount Surprise, and we will return to Undara in the morning.

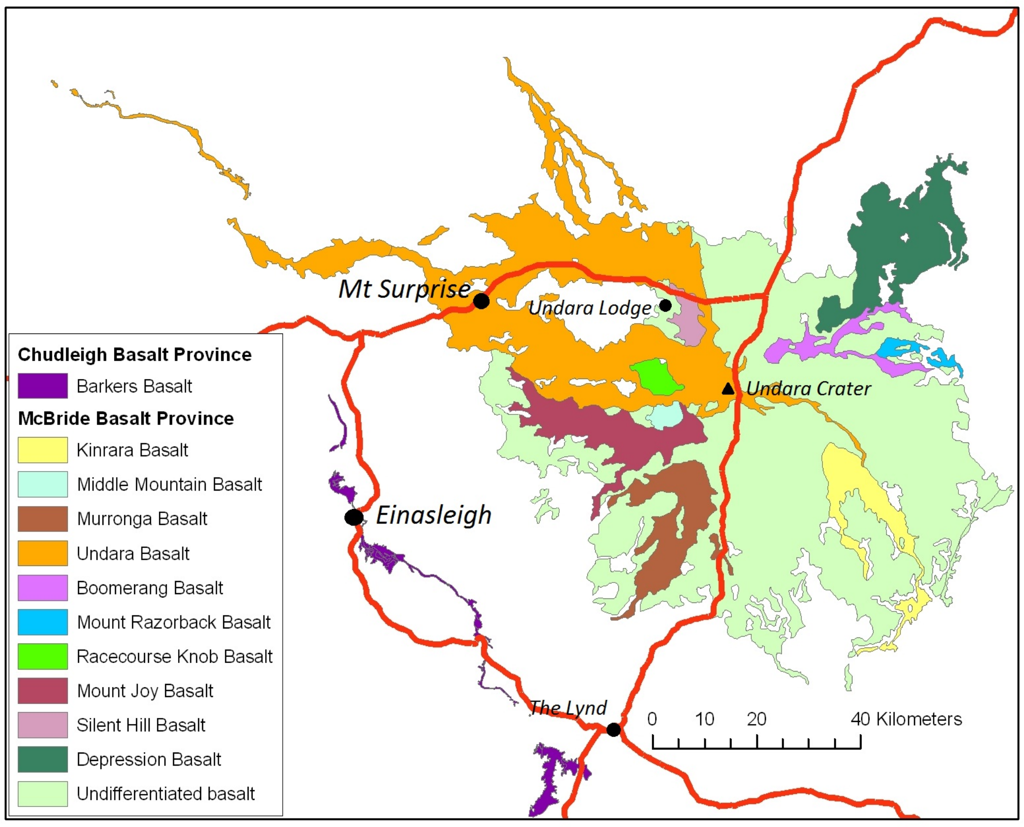


Figure 17: Distribution of Pliocene to Recent basalts in the Einasleigh-Mount Surprise area.

Day Four

Stop 10b: Guided tour of the Undara lava tubes

More than 60 caves and arches have been discovered in the Undara Lava Tube System. Most are less than 200m long, but one can be followed for 1.3 km. The main branch of the lava tube system extends more than 110 km, and includes a level ridge known as The Wall, which stands more than 20m above the surrounding country and is considered to be analogous with similar features observed on the Moon. It formed where lava flowing along an original channel built up levees.

Various interesting features can be observed within the lava tubes. Horizontal or near horizontal ledges, termed lava level lines, on tube walls reflect periods of flow at a constant height in the tube, the width of any ledge reflecting how long the lava was flowing at that height. Surges of lava left multi-layered linings on the tube walls. Above the flow tube walls and roofs became glazed, often re-melting and dripping to form fragile, hollow straw stalactites and more robust, triangular lavacicles. Dribbles of lava ran down some walls and occasionally were deflected from vertical, possibly by the blast furnace effect of an adjacent skylight.

Lava ponds formed in line with, or adjacent to, some sections of the lava channel. Repeated small overflows and spatter at the pond margins built up levees higher than the surrounding country. While the tube was flowing, the ponds remained full, their surfaces crusting as they cooled. When eruption ceased, the ponds drained back into the tube leaving depressions. These have since created fertile pockets where rainforest plant, insect and animal species thrive. The rainforest species in these depressions are found in Madagascar and East Africa, having evolved from the time of Gondwana.

Figure 18: View of the McBride Basalt Province from The Bluff, showing some of the volcanoes on the horizon

Figure 19: Entrance to one of the large lava tubes from a collapsed section, Undara National Park

Undara to Newcastle Range

We return to the Gulf Developmental Road and continue 38 km westwards to Mount Surprise following a branch of the Undara Basalt that flowed around the northern side of the range formed by the Whitewater Granite. The Undara Basalt continues for another 8 km to near Junction Creek. Just before the edge of the flow is reached, the road crosses the southern part of The Wall. The western side of the wall is more conspicuous, possibly due to damming of slightly later basalt flows against the eastern side.

From Junction Creek westwards, the road traverses the Paleoproterozoic Einasleigh Metamorphics, which here include mica schist, quartzite, biotite gneiss and migmatite that passes into nebulitic granite. The metamorphic rocks have been subdivided based on different proportions of these rocks as reflected in their airborne geophysical (radiometric and magnetic) responses. Amphibolite and metagabbro sills and stocks are also present.

Continuing westwards, we cross the Einasleigh River and about 15 km farther on, pass out of the metamorphic rocks into the Silurian White Springs Granodiorite, which consists of grey equigranular to porphyritic muscovite-biotite and biotite granodiorite. It is a component of the voluminous Silurian (ca. 426 Ma) White Springs Supersuite — the dominant Silurian–Devonian granite supersuite in the Georgetown region. The supersuite is part of the Pama Igneous Association (Bain & Draper, 1997; Withnall & Henderson, 2012).

The Newcastle Range is the topographic expression of the Newcastle Range Volcanic Group, which represents one of the most extensive remnants of Carboniferous extrusive rocks in north Queensland (Withnall & others, 1997b). It is exceeded in extent and thickness only by the Featherbed Volcanic Group near Chillagoe. It consists of a main north–south elongated composite subsidence structure with a prominent lobe to the east.

Rocks of the Newcastle Range Volcanic Group are predominantly ignimbrite, together with minor lava, unwelded pyroclastic rocks and rare sedimentary rocks. The primary eruptive rocks range in composition from rhyolite to andesite (and possibly very rare basalt) with rhyolitic rocks constituting about 85–90%, dacitic rocks about 5–10%, and andesite the remainder of the preserved volume. These rocks have been divided into four subgroups according to which part of the composite subsidence structure they occupy:

- The Wirra Volcanic Subgroup, which forms the southern lobe of the main north–south elongated portion of the composite subsidence structure (Wirra Cauldron)
- The Kungaree Volcanic Subgroup, which forms a north–south ‘isthmus’ (Kungaree Trough) connecting the southern and northern lobes of the composite subsidence structure
- The Namarrong Volcanic Subgroup, which forms the rounded northern lobe of the main structure (Namarrong Cauldron)
- The Eveleigh Volcanic Subgroup, which forms the eastern lobe (Eveleigh Cauldron).

Virtually all the rocks of the Newcastle Range Volcanic Group were erupted and emplaced in a subaerial environment. Volcaniclastic rocks at the base of the Wirra sequence contain lenses of plant fossil-bearing arenaceous limestone, probably deposited in a restricted lacustrine environment, and other sedimentary rocks intercalated within the volcanics are fluviatile, shallow lacustrine, or mass-flow in origin.

The Gulf Developmental Road crosses the 'isthmus', which appears to be an elongate trough or rift-like structure delineated by approximately north-trending fracture systems, and is less well-defined than the other cauldron-like lobes.

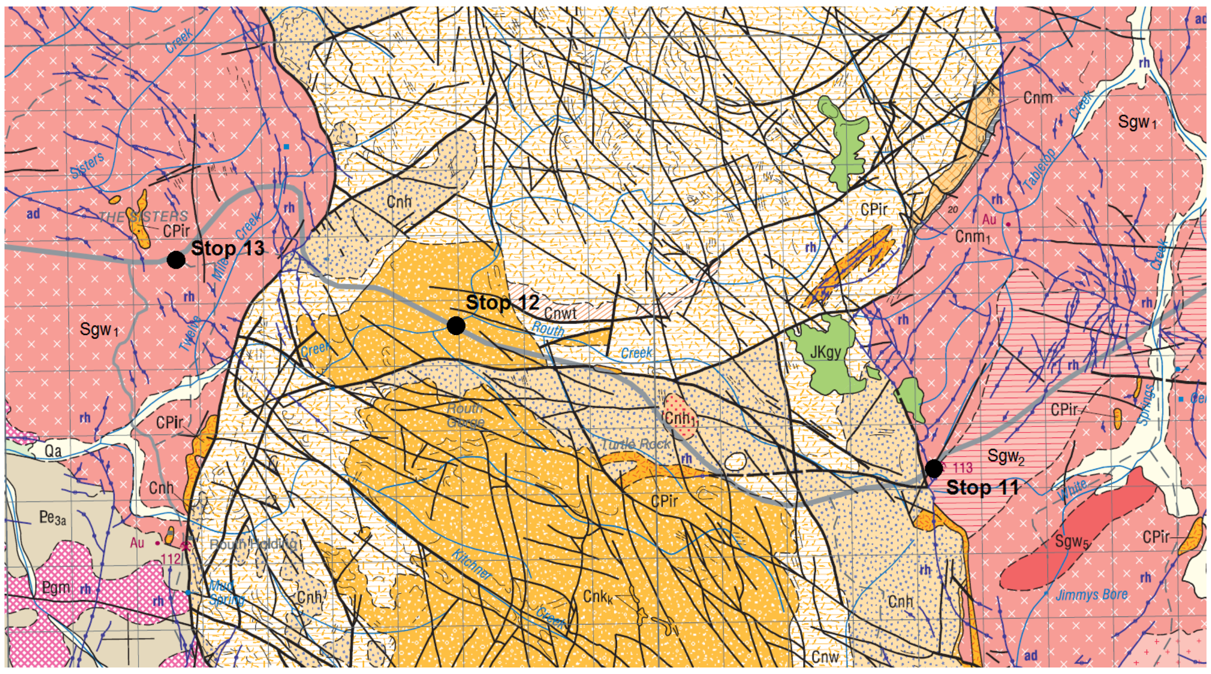


Figure 20: Geology of part of the Kungaree Trough in the Newcastle Range. Units of note are: units prefixed by Sgw – White Springs Granodiorite; Cnh – Routh Dacite; Cnk – Kitchen Creek Rhyolite; Cnw – Corkscrew Rhyolite; CPir – intrusive rhyolite. Proterozoic units in bottom left corner are Pgm – Mistletoe Granite and Pe_{3a} – Einasleigh Metamorphics. From Georgetown 1:100 000 Geological Sheet. Grid squares are 1 km.

Stop 11: Eastern escarpment of the Newcastle Range, Gulf Developmental Road, UTM 54K 794250 7973350, Figure 20

A road cutting on the northern side of the road exposes a steeply dipping fault and dyke zone along the eastern edge of the Newcastle Range (Figure 21). The zone contains pink porphyritic microgranite, and younger altered green microdiorite or andesite dykes, and a wedge-shaped area of fluoritised microgranite-dacite breccia. The breccia was prospected by Pioneer Minerals in 1972 and besides fluorite, contains up to 150 ppm uranium and 710 ppm molybdenum. This U–F–Mo association is common in the Carboniferous volcanic rocks of the Kennedy Igneous Association.

To the east of the fault zone the cutting exposes weathered, porphyritic biotite granodiorite of the Silurian White Springs Granodiorite. Routh Dacite, one of the components of the Carboniferous Newcastle Range Volcanic Group, is exposed in the next cutting to the west. The locality provides good views to the south along the eastern side of the main part of the Newcastle Range and eastwards to the eastern lobe of the range (or Eveleigh cauldron subsidence structure).

The cutting is on a busy road. Please take care crossing the road, and ensure that you stand well clear of the carriage-way — and wear your visibility vest. Remember to look both ways — cars drive on the left hand side of the road in Australia.

The fact that the Routh Dacite is one of the lower units of the succession, and the presence of stratigraphic, rather than faulted contacts only 3–4 km north of the Gulf Developmental Road, suggests that a sag-like geometry rather than a rift is more appropriate and that the throw on the eastern-bounding fault is relatively small.

Figure 21: Faulted contact of the Newcastle Range Volcanic Group at Stop 11. The person to the right is examining an altered basalt dyke that separates the White Springs Granodiorite from a large microgranite dyke to the left

Figure 22: Crystal-rich ignimbrite in Routh Creek at Stop 12, showing abundant crystal fragments and elongate fiamme

Stop 12: Routh Creek bridge, Gulf Developmental Road, UTM 54K 786835 7975624. 7975624, Figure 20

We continue west for another 8.5 km to the bridge over Routh Creek. In the bed of Routh Creek, purplish brown, moderately crystal-rich rhyolitic ignimbrite with a well-developed eutaxitic fabric defined by flattened pumice fragments or fiamme is well exposed (Figure 22). Crystal fragments include both quartz and feldspar and some chlorite aggregates are present locally. This outcrop is part of a single sheet of welded ignimbrite up to 180 m thick mapped as Kitchen Creek Rhyolite of the Kungaree Volcanic Subgroup.

Routh Creek towards Georgetown

About 3 km west, the road descends down the western scarp of the Newcastle Range, alongside a spectacular rhyolite dyke that was intruded into the western bounding fault. The road then traverses more of the underlying Silurian White Springs Granodiorite for about 9 km.

Stop 13: Gulf Developmental Road, about 3 km west of the Newcastle Range, UTM 54K 782850 7976750, Figure 20

Outcrops of the grey medium-grained equigranular to porphyritic biotite granodiorite of White Springs Granodiorite will be briefly examined here if time permits. Particular feature to note is its relatively unstrained nature compared with the Mesoproterozoic granites to be examined at the next two stops. The large relatively equant quartz grains are also a feature of the Silurian granites in this area. The White Springs Granodiorite is metaluminous to mildly peraluminous and is considered to be I-type.

Further west along the road, the contact of the White Springs Granodiorite with Einasleigh Metamorphics is at O'Brien's Creek and the road then passes over weathered gneiss, amphibolite and migmatite with sporadic leucogranite for about 4 km before passing into the Mesoproterozoic Forsayth Batholith. The Forsayth Batholith is a large composite batholith with eight major granite units that form multiple plutons commonly separated by screens and roof pendants of metamorphic rocks (Withnall & others, 1997b).

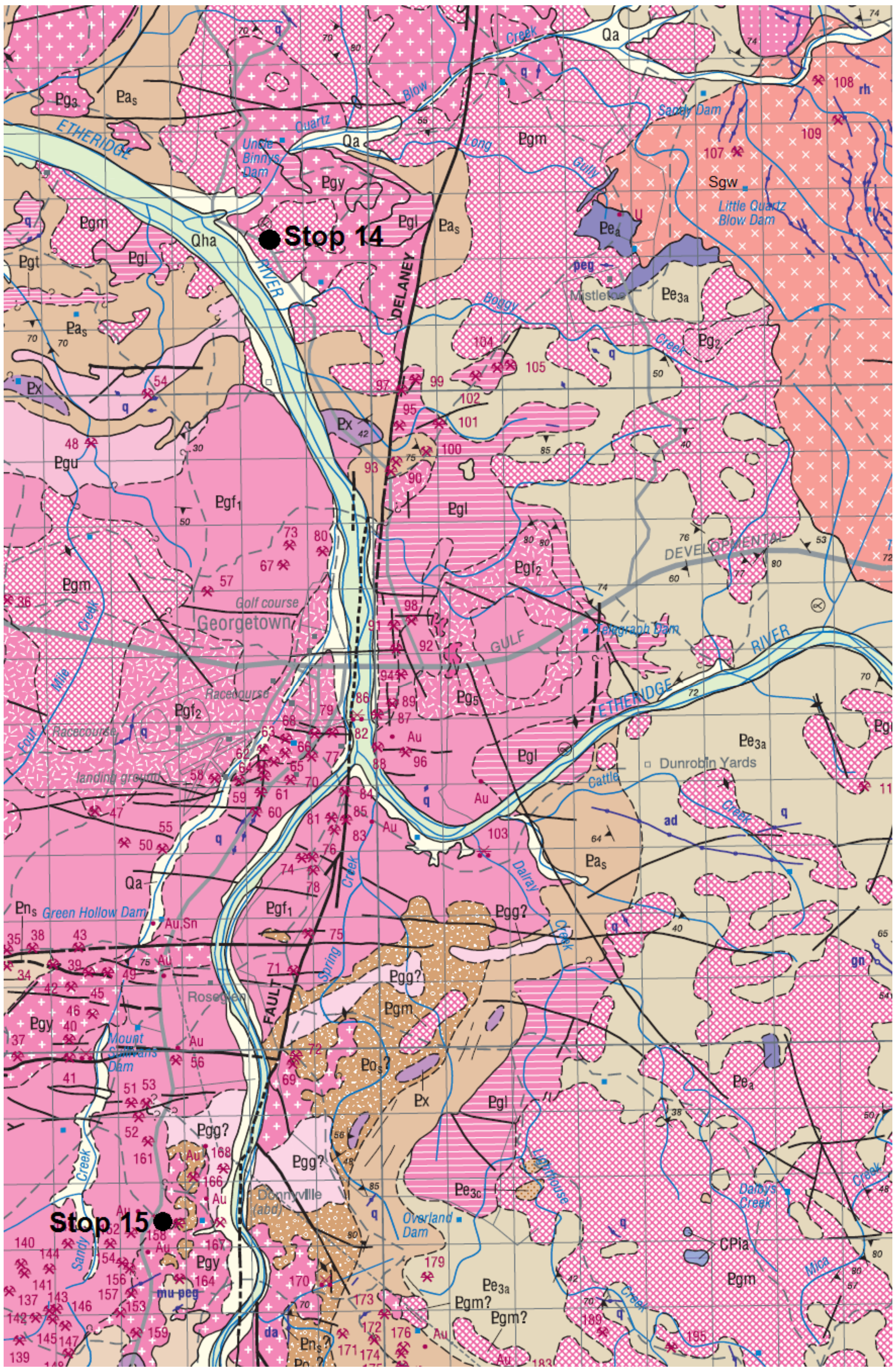


Figure 23: Geology in the vicinity of Georgetown. Units of note are: Sgw – White Springs Granodiorite; Ᵽgm – Mistletoe Granite, Ᵽgl – Lighthouse Granite, Ᵽgg – Goldsmiths Granite, Ᵽgy – Delaney Granite, Ᵽgf$_1$ and Ᵽgf$_2$ – phases of Forsayth Granite. Ᵽo$_s$ – Corbett Formation, Ᵽa$_s$ – Daniel Creek Formation, Ᵽx – Cobbold Metadolerite, Ᵽe$_{3a}$ – Einasleigh Metamorphics. From Georgetown 1:100 000 Geological Sheet. Grid squares are 1 km.

Figure 24. Schlieren-rich muscovite-biotite granite of the Mistletoe Granite at Stop 14.

Figure 25. Porphyritic biotite granite of the Forsayth Granite at Stop 15. The porphyritic granite is cut by dykes of finer grained muscovite-biotite granite from the adjacent Delaney Granite.

Stop 14: Near Quartz Blow Creek on the Georgetown–Ironhurst Road, UTM 54K 768230 7982480, Figures 23 and 24

Just east of the bridge over the Etheridge River, take the Ironhurst road to the north for 7.5 km to just south of Quartz Blow Creek.

Outcrops to the east of the road are mapped as Mistletoe Granite, which is one of the units within the Mesoproterozoic Forsayth Batholith. The outcrops consist of medium-grained muscovite-biotite granite containing abundant biotite-rich schlieren and xenoliths of gneiss, amphibolite and vein quartz, which are interpreted as restite. The granite, like most of the Forsayth Batholith, is strongly peraluminous and considered to be S-type. East of the Newcastle Range, the Einasleigh Metamorphics in many places grade into nebulitic migmatites that resemble the Mistletoe Granite. However, this area represents a higher-level in the crust, and the melts were probably mobilised upwards and form mappable plutons intruding the surrounding metamorphic rocks. This site was sampled for isotopic dating and yielded a U–Pb zircon (SHRIMP) age of 1544 ± 7 Ma.

We will return to Georgetown and turn left just across the bridge and take the Forsayth road for about 9 km south. The road traverses other granites of the Forsayth Batholith, in particular its most characteristic unit the Forsayth Granite. The granites of the batholith are mostly grey, variably porphyritic muscovite-biotite to biotite granite. The different units can be distinguished texturally and also by their radiometric response in airborne geophysical images, which has aided in their mapping. All are high in potassium, but show variations in the abundance of uranium and thorium.

Stop 15: Georgetown–Forsayth Road, 9 km south of Georgetown, UTM 54K 766600 7967450, Figures 23 and 25.

At this locality two units of the Forsayth Batholith are exposed. Most of the outcrops here consist of the Forsayth Granite, which is a dark grey, porphyritic, medium to coarse-grained biotite granite with abundant, grey, tabular K-feldspar megacrysts to 2cm long. In places there are irregular dykes and veins of a pale grey, medium-grained muscovite-biotite granite containing very small K-feldspar phenocrysts. These are probably derived from the Delaney Granite, another component of the batholith, which is mapped to the south of here.

On our return to Georgetown, if there is time, we will stop for an hour to visit the Ted Elliott Mineral Collection at the Etheridge Shire Council's TerrEstrial Centre. The Collection comprises over 4500 specimens, displayed throughout nine themed rooms, ranging from local mining to specimens from around the world. This collection is reputed to be the most detailed and comprehensive private collection in Australia.

Overnight in Georgetown

Georgetown has a population of about 250 and is the administrative centre of Etheridge Shire. The main industry is beef production, but the shire has also embraced outback tourism. In the past it was also an important gold mining centre.

Alluvial gold was discovered in the Etheridge River at the present site of Georgetown in 1869 by Richard Daintree, the first government geologist for North Queensland. The township, named Georgetown in honour of the first gold commissioner, Howard St George, became the administrative centre of the Etheridge Gold and Mineral Field. The alluvial gold attracted a rush of prospectors, estimated at up to 3000 at its peak. This number was short-lived however, as the miners were soon drawn to more rewarding sites such as the Palmer River and Hodgkinson fields. Many returned in 1878 and activity increased, particularly after the introduction of English capital in the 1880s. Lode mining was established at a number of centres, including Georgetown, Durham, Cumberland, Forsayth, Castleton, Western Creek and Lane Creek, Overcapitalisation and high management expenses eventually led to the failure of most of these ventures. The peak production was in 1893 when 900 kg of gold bullion was produced. Production then declined as reserves of oxidised ore were depleted. Cyanidation, introduced in 1894, did little to revive production. Total production from reef mining in the Etheridge Field was about 14 000 kg of bullion in addition to about 3400 kg of fine gold from smelted ore. Alluvial production is unknown, but estimates suggest more than 5000 kg.

The Almaden to Forsayth railway was completed in 1909 but it was not extended to Georgetown. The line did prolong the life of some mines in the area. The Chillagoe Mining Company, which owned the railway, carried out prospecting particularly for base metals, but ceased operations when their smelter closed in 1914. The Queensland Government took over operation of the railway and smelter in 1919, but mining in the Etheridge Field had already virtually ceased.

A revival of small-scale mining in the 1930s was mainly as a result of the Great Depression and a revaluation of gold. The Havelock near Forsayth, and City of Glasgow near Georgetown, were the last underground gold mines worked in the area and closed in 1950 and 1953, respectively. Since 1962 numerous companies have investigated the known gold-quartz reefs of the Etheridge Goldfield, and in recent years, some have been worked by small opencut mines, with the ore being treated at a central plant by heap leaching. The last such operation was by Deutsche Rohstoff AG in 2010–11.

The majority of reefs are within Mesoproterozoic granites of the Forsayth Batholith, although there are also a significant number of small deposits in amphibolite facies metasedimentary rocks adjacent to the granites, particularly between Forsayth and Georgetown. The reefs are mineralised quartz veins, 100 mm to 5 m wide, with well-defined walls in generally steeply dipping fracture or shear zones in granite, schist or metabasite. Some reefs comprise a solitary quartz vein, others a zone of subparallel veins and stringers, sometimes flanking a large central vein. The smallest deposits are generally in a network of thin quartz stringers.

The shallow (10 to 30m) oxidised zones of the mineralised reefs consist of iron-stained quartz and limonitic gossan, locally with cerussite, malachite and azurite. Below the water table, the reefs are generally strongly pyritic, and galena, sphalerite and chalcopyrite comprise up to 50% of total sulphides, although only a few mines produced significant quantities of base metals.

As well as being spatially associated with Mesoproterozoic granites, almost all of the deposits lie within a belt of late Palaeozoic igneous rocks. However, isotopic dating of the altered wallrocks of deposits regarded as generally representative of the field has yielded only Silurian to Devonian ages (398 to 426Ma), indicating that the deposits are probably genetically related to I-type granites of the Pama Igneous Association.

Day Five

This morning we continue along the road to Forsayth. About 2 km from Stop 14, we pass into a belt of metamorphic rocks that separate the northern and southern parts of the batholith. The soil colour changes to reddish and metadolerite and metagabbro crop out in places.

About 16 km from Georgetown, turn off the main road and take the road to Flat Creek homestead for about 10 km. Rocks exposed in this area consist of mostly fine-grained metasedimentary rocks of the Lane Creek Formation, part of the Paleoproterozoic Etheridge Group (Withnall & others, 1997b; Withnall & Henderson, 2012). The rocks are commonly carbonaceous as evidenced by the greyish soil in places. They are intruded by metadolerite and metagabbro sills assigned to the Cobbold Metadolerite. The Cobbold Metadolerite has been dated at 1655 ± 5 Ma (Black & others, 1998) and was probably intruded soon after deposition of the Lane Creek Formation as it does not intrude the conformably overlying units.

Stop 16: Western Creek area along road to Flat Creek homestead, UTM 54K 757785 7956580, Figure 26

Strongly carbonaceous metasiltstone and fine-grained mica schist of the Lane Creek Formation is exposed here. The metamorphic grade is lower amphibolite facies and chiastolite porphyroblasts are relatively common. The main foliation is a fine differentiated crenulation cleavage.

Stop 17: Western Creek area along road to Flat Creek homestead, UTM 54K 758363 7957220, Figure 26

About 500 m back towards the main road, we will stop to examine outcrop of Cobbold Metadolerite. The metadolerite consists mostly of plagioclase and hornblende. The rocks here are not foliated and still retain an igneous appearance, although plagioclase is mostly recrystallised. However, in places the hornblende has a blastophitic texture, pseudomorphing the clinopyroxene of the protolith.

The metadolerite sills outline basin-and-dome structures produced by interference of the two major regional folding events. Large 'blows' of barren quartz that occur nearby are relatively common in the sills, probably being emplaced into fractures formed in the relatively massive and brittle metadolerite during the folding.

Western Creek to Einasleigh

After returning to the main road, we drive south to Forsayth through topography characterised by granite tors in the southern part of the Forsayth Batholith. Forsayth was another gold mining centre and was established as the terminus of the railway constructed by the Chillagoe Company to supply ore for its smelter in 1909. Mills were built at several of the mines near Forsayth, but they were short-lived. Nevertheless, mines around Forsayth continued to rail small parcels of ore to Chillagoe until the smelter finally closed in 1943. The railroad is still in service as a tourist railway.

From Forsayth, we drive east across more of the Forsayth Batholith for about 8 km before passing back into the Lane Creek Formation, climbing gradually onto the Newcastle Range which here is largely covered by Jurassic to Cretaceous fluviatile to shallow marine sedimentary rocks forming a laterite-capped plateau. Ignimbrite and andesite of the Newcastle Range Volcanic Group are exposed on the eastern scarp. The road descends towards the Einasleigh River through Einasleigh Metamorphics, which form a triangular embayment between the fault-bounded margins of the Wirra and Eveleigh cauldrons to the south and north respectively.

The township of Einasleigh, originally named Copperfield, was established in 1900 near the Einasleigh Company's copper mine. After the closure of the mine in the 1920s, the township almost disappeared and was saved from extinction only by its location on the railway.

Discovered in 1866 by Richard Daintree the first government geologist for North Queensland, the Einasleigh copper deposit was one of the earliest mineral discoveries in Queensland. The deposit was too remote to develop and was abandoned and virtually forgotten. The Chillagoe Company rediscovered the Einasleigh shaft when exploring the area and began developing it in 1900 through its subsidiary, the

Einasleigh Copper Mines Company. Small blast furnaces were erected for smelting in 1902, but until the opening of the Etheridge Railway in 1910 operations were uneconomical because of high transport costs. The mine closed when the Chillagoe Smelters were shut down in 1914. Acquired by the Queensland Government in 1919 as part of the assets of the Chillagoe Company, it returned to full production, supplying the reopened smelters. As the Einasleigh State Mine, it finally closed in 1922 as a result of depleted ore reserves and a drop in the world copper price. It produced 8237 t of copper, 4083 kg of silver and 71.2 kg of gold from 136 412 t of ore.

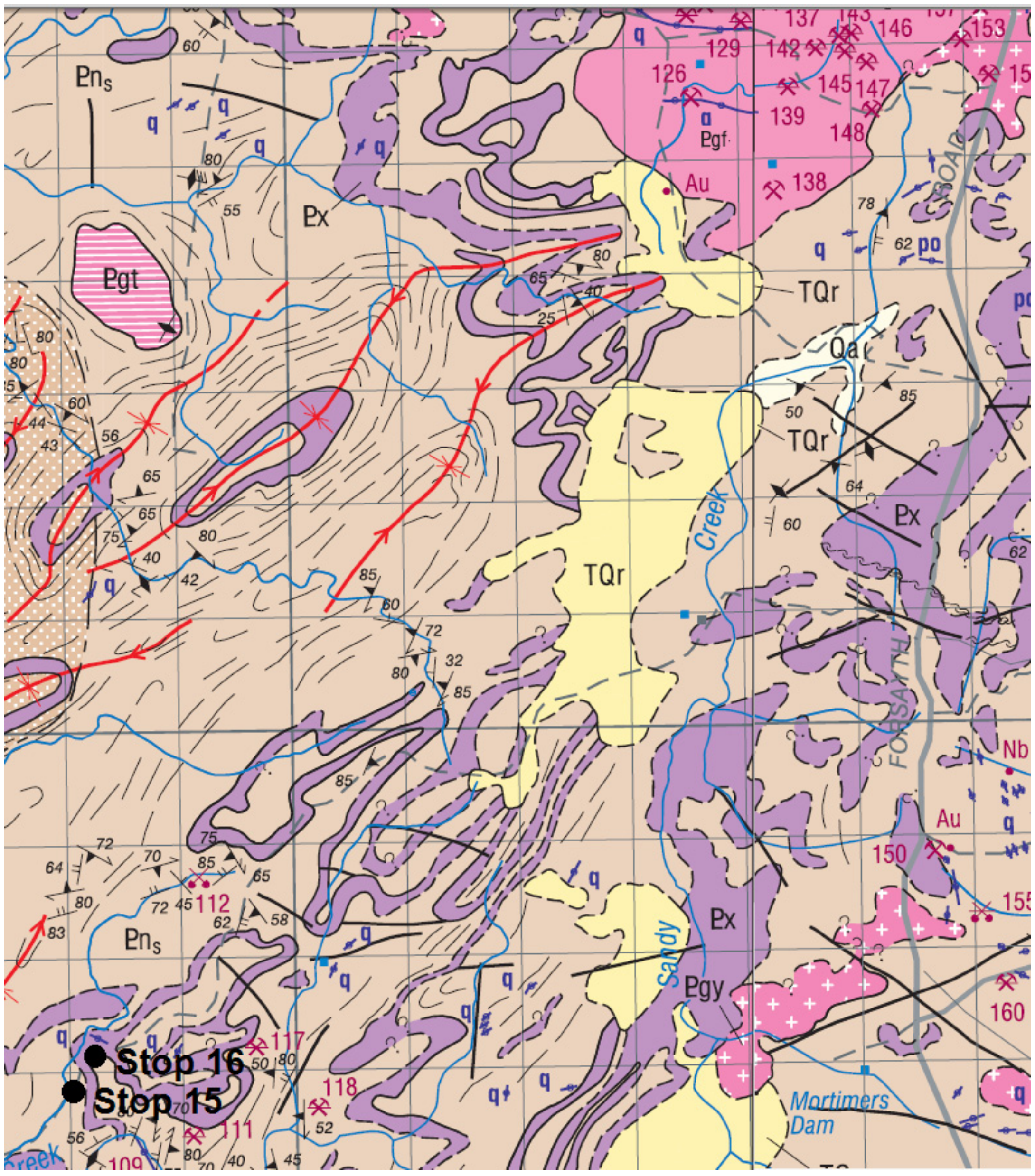


Figure 26: Geology in the vicinity of Western Creek area. Units of note are: Qa – alluvium, TQr – colluvium and older alluvium, Ꝑgt – Talbot Creek Trondhjemite, Ꝑgy – Delaney Granite, Ꝑgf –Forsayth Granite. Ꝑn$_s$ – Lane Creek Formation, Ꝑx – Cobbold Metadolerite. From Forest Home and Georgetown 1:100 000 Geological Sheets. Grid squares are 1 km.

Recently, the Einasleigh mine was investigated by Copper Strike Ltd in conjunction with a number of other copper and zinc–lead deposits in the surrounding area. Based on this work, the Einasleigh deposit has an Indicated Resource of 0.5 Mt at 4.0% Cu, 18 g/t Ag and 0.22g/t Au, and an Inferred Resource of 0.6 Mt at 1.9% Cu, 8 g/t Ag & 0.10g/t Au. A feasibility study examining the joint development of the copper and the zinc–lead deposits was completed in mid-2009. The project was acquired by Karara Limited in 2011 prior to it going into receivership.

The Einasleigh deposit is one of numerous small base metal occurrences through the Einasleigh Metamorphics that are generally thought to be stratabound. In regional terms the deposits appear to be concentrated at a common stratigraphic level within the Einasleigh Metamorphics, at the transition between a lower, dominantly calcareous psammitic sequence and a psammopelitic sequence. Smaller vein deposits represent remobilised portions of stratabound deposits.

Mineralisation appears to be controlled by intersecting faults and pre-existing folded architecture, and occurs as infill of dilation zones (milled breccia chambers) along and within faults and as replacement of favourable (calc-silicate?) horizons. Two styles of mineralisation are present: tabular breccia bodies with high copper grades in a semi-massive to massive sulphide matrix (pyrrhotite–chalcopyrite–pyrite–magnetite); and lower grade skarn-like replacements in thin tabular stratiform bodies with stringer and disseminated sulphides (Lees & Buckle, 2009).

Stop 18: Copperfield Gorge, Einasleigh, UTM 55K 193500 7950850, Figures 20 and 21

On reaching Einasleigh, we will drive past the hotel to a small picnic shelter on the edge of the Copperfield River. The Copperfield River cuts a small gorge through several basalt flows. A black, highly vesicular flow overlies two other grey, less vesicular flows with prominent cooling columns (Figure 21).

The basalt flows at Einasleigh can be traced up the Einasleigh River to a crater in its headwaters known as Barkers Crater. K–Ar dating of basalt at Barkers Crater and at Einasleigh (from the middle flow) has yielded the same age (~0.26Ma), and although alluvium from the river has obscured the basalt for part of its course, continuity can be verified from airborne magnetic data indicating that the lava from Barkers Crater flowed approximately 160 km, a similar distance to that from the Undara Crater. In many places, the basalt appears to have been confined to the former channel of the Einasleigh River, but in places such as Einasleigh and farther south near Lyndhurst homestead, it spread out to form a flat plain. The section exposed in the wall of the gorge indicates that the basalt was erupted in several pulses, although it is difficult to estimate the time between flows.

Lunch will be taken at the Copperfield Gorge picnic site, although participants may like to experience the hospitality of the Einasleigh Hotel. A highlight is the reproduction of the painting *Chloe*, the original of which hangs in Young & Jacksons Hotel, one of Melbourne’s oldest watering holes.

Stop 19: Einasleigh River, near the Einasleigh copper mine, UTM 55K 193900 7951300, Figures 27, 29 and 30.

Large exposures in the bed of the Einasleigh River below the Einasleigh mine are the type locality of the Einasleigh Metamorphics and are representative of the psammo-pelitic facies within the unit.

Access to the river bed is from the mine site but take care scrambling down the loose rubble.

The rocks exposed consist of well-layered, multiply deformed biotite gneiss, mica schist and quartzite cut by amphibolite and later leucogranite and pegmatite dykes. The layering in the gneiss probably partly reflects an original sedimentary layering as it is parallel to the gross layering represented by the quartzite. However, it is parallel to a foliation defined by alignment of mica and has probably been modified by tectonic processes.

The numerous layers of amphibolite probably represent sills or dykes of tholeiitic dolerite. Elsewhere in the Einasleigh area, the amphibolite bodies have been dated at ~1675Ma by the SHRIMP U-Pb method on zircon (Black & others, 1998). The amphibolite locally appears to cut across the layering and layer-parallel foliation suggesting that these formed prior to the emplacement of the mafic rocks and could represent a metamorphic event, prior to 1675Ma. Zircons in the mafic rocks also show metamorphic rims, and along with zircons from the leucogranite dykes have yielded ages of ~1560Ma, dating the peak of metamorphism.

The metamorphism was largely in the upper amphibolite facies, but locally assemblages in some of the mafic rocks contain orthopyroxene, indicating that the metamorphic grade reached granulite facies. Later retrogressive metamorphism is evident and most of the sillimanite in the pelitic rocks has been replaced by fine-grained muscovite, and garnet is retrogressed to chlorite.

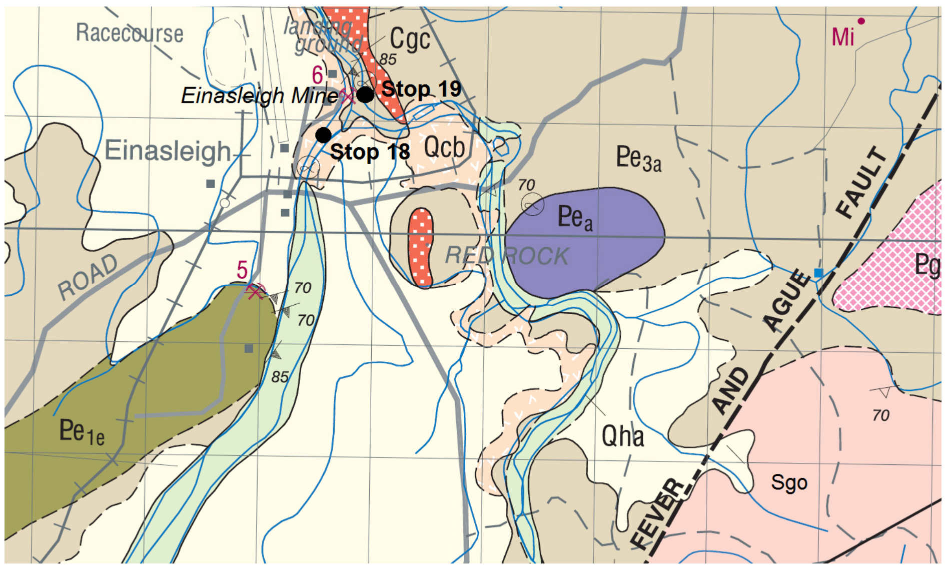


Figure 27: Geology of the Einasleigh area. Units prefixed by Ꝑe – Einasleigh Metamorphics (3a – biotite gneiss dominated, 1e – calc-silicate gneiss, a – amphibolite and mafic granulite), Sgo – Oak River Granodiorite, Cgc – Caterpillar Range Microgranite, Qcb – Barkers Basalt; Qa – alluvium; Qha – active river channels. From Einasleigh 1:100 000 Geological Sheet. Grid squares are 1 km.

Figure 28: Copperfield Gorge at Einasleigh showing columnar jointed Pleistocene basalt (Barkers Basalt). The ridge in the background is formed from the Carboniferous Caterpillar Range Microgranite.

Figure 29: Einasleigh Metamorphics at Stop 19, showing banded biotite gneiss and disrupted amphibolite dykes

Figure 30: Einasleigh Metamorphics at Stop 19, showing folded biotite gneiss and discontinuous pegmatite veins

The layer-parallel foliation has locally been tightly folded and a new foliation and differentiated layering has developed parallel to the axial planes of these folds.

The large ridge on the eastern side of the river, and the large hill to the south (known as Red Rock) consist of porphyritic microgranite, containing quartz, feldspar and sparse hornblende and biotite in a fine-grained reddish quartz-feldspar groundmass. This rock is assigned to the Caterpillar Range Microgranite and is Carboniferous and related to the Newcastle Range Volcanic Group. It forms a series of elongate bodies within a polygonal fracture system to the south-east of the Eveleigh cauldron subsidence structure.

Einasleigh to The Oasis

Leaving Einasleigh we travel via the Gregory Developmental Road towards the Lynd Junction. The first 50 km of the route crosses the Copperfield Batholith of which the main component is the Oak River Granodiorite. It has multiple phases but they are difficult to map out because of the poor outcrop. The rocks are part of the Pama Igneous Association.

Basalt at the Einasleigh River crossing is part of the same set of flows observed at Einasleigh. South-east of crossing, we pass back into Einasleigh Metamorphics, although exposure is still poor.

The section of road between about 15 km and 23.5 km from the Einasleigh River crosses a belt of Einasleigh Metamorphics bounded by the Lynd Mylonite Zone on the east. The rocks within this belt along the road consist of a calc-silicate gneiss facies within the Einasleigh Metamorphics and the Mesoproterozoic Mywyn Granite, again poorly exposed, but which can be recognised on airborne geophysical images by their magnetic and radiometric response.

The Lynd Mylonite Zone (Figure 31) has been interpreted as the eastern limit of Paleoproterozoic to Mesoproterozoic rocks in this area, and therefore defining the Tasman Line (Fergusson & others, 2007). Rocks west of the Lynd Mylonite Zone contain ~1700Ma detrital zircon and metamorphic rims of ~1560Ma (Black & others, 2005) and are assigned to the Einasleigh Metamorphics. Rocks to the east of the Lynd Mylonite Zone contain late Neoproterozoic detrital zircon and have metamorphic overgrowths dated at ~480Ma and are therefore late Neoproterozoic or Early Cambrian and have been assigned to the Oasis Metamorphics. These age relationships combined with a westerly dip interpreted from the deep crustal seismic survey (Korsch & others, in press) would suggest that the Lynd Mylonite Zone is a thrust.

Where the Lynd Mylonite Zone is interpolated to cross the road, outcrop is non-existent, but it has been observed to the north and south. The best outcrops are in McKinnons Creek about 6 km south of the road where mylonitised granite and gneiss crop out. The foliation is vertical with a down-dip stretching lineation and S-C fabrics that indicate east-block-up. This conflicts with the interpretation of the Lynd Mylonite Zone as a thrust, and suggests a complex movement history.

Immediately east of the Lynd Mylonite Zone, the road traverses the Silurian McKinnons Creek Granite, which is very poorly exposed.

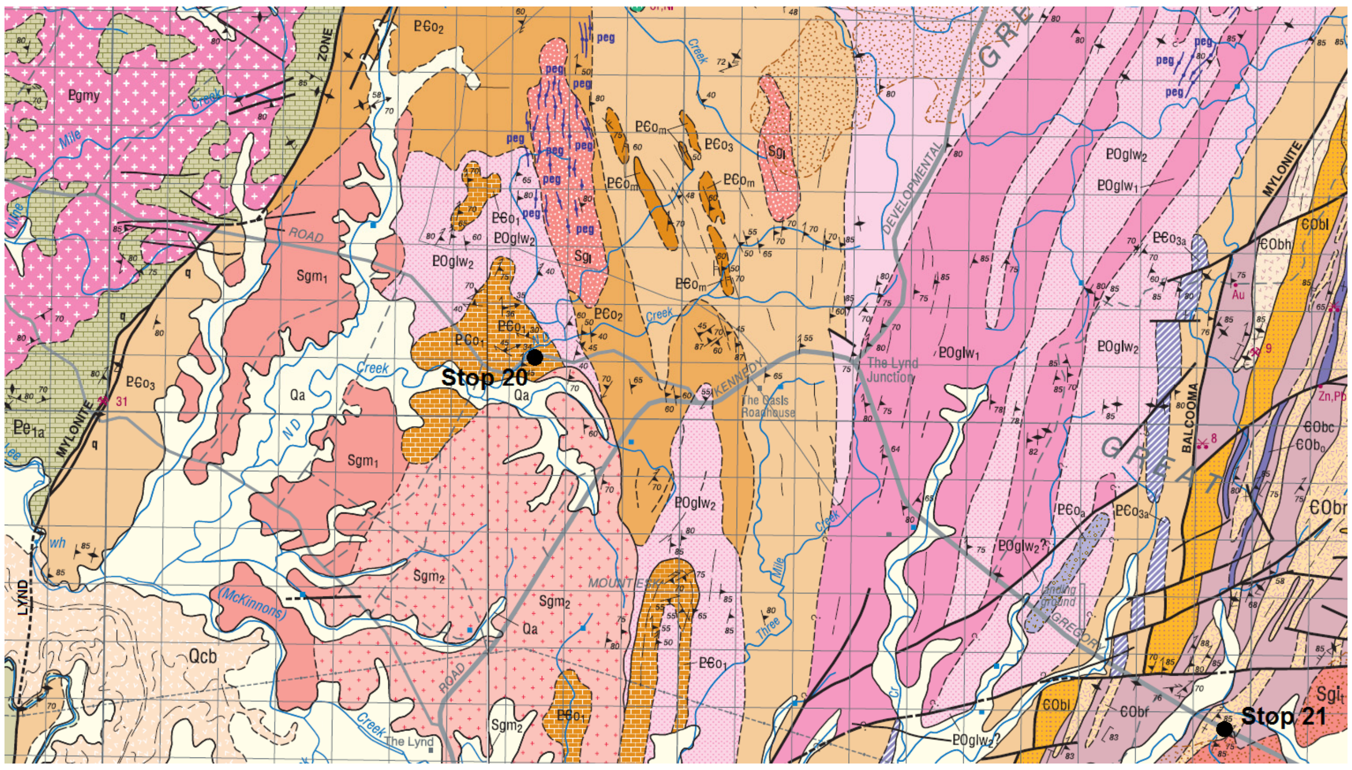


Figure 31: Geology of The Oasis area across the Lynd Mylonite Zone (Tasman Line). Units to note are: west of the Lynd Mylonite Zone (LMZ) are Ᵽe$_{1a}$ – Einasleigh Metamorphics (calc-silicate facies) and Ᵽgmy – Mesoproterozoic Mywyn Granite. Units east of LMZ are prefixed by: PꞒo – Neoproterozoic or Cambrian Oasis Metamorphics, ꞒOglw – Ordovician Lynwater Complex and Sgm – Silurian McKinnons Creek Granite. Units of the Cambro-Ordovician Balcooma Metavolcanics (prefixed by ꞒOb) lie to the east of the Balcooma Mylonite Zone. From Einasleigh and Conjuboy 1:100 000 Geological Sheets. Grid squares are 1 km.

Stop 20: Gregory Developmental Road, just east of ND Creek, UTM 55K 237150 7910820, Figures 31–33

This site on the southern side of the road consists of calc-silicate granofels, probably representing a calcareous sandstone or siltstone protolith. However, it occurs within a succession that has been dated as probably Cambrian (Fergusson & others, 2007 — see above) and was also assumed to have a similar age. Recent SHRIMP dating of both zircon and titanite from the granofels, however, indicates a metamorphic age of 1600 Ma, and suggests it is a basement package within the Oasis Metamorphics. It resembles calc-silicate gneiss and granofels that occurs within the Einasleigh Metamorphics.

The granofels contains two foliations. The earlier layering/foliation is the most obvious structure and is defined by compositional layering and aligned clinopyroxene and hornblende in calc-silicate gneiss, biotite, quartz and feldspar in pegmatite, biotite and quartz in schist and gneiss, and amphibole in amphibolite. The compositional layering probably reflects sedimentary layers, but could be entirely a differentiated layering. The main foliation (S_g) is locally tightly folded by plunging F_2 and has an axial plane foliation developed in places (Figure 25). Amphibolite metamorphism accompanied the deformation in the Oasis Metamorphics with granitic veins and segregations (Figure 26) formed subparallel to S_g and also along the axial planes of the local mesoscopic F_2 folds.

Figure 32: Banded calc-silicate granofels in the Oasis Metamorphics at Stop 20, showing a mineral foliation axial planar to folded compositional layering.

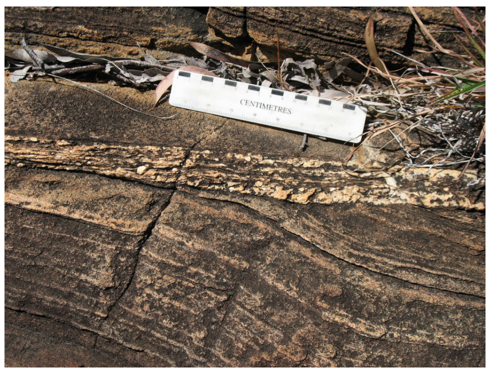


Figure 33: Banded calc-silicate granofels in the Oasis Metamorphics at Stop 20, showing a foliated leucogranite vein cutting across the layering.

The Oasis to Greenvale

About 3.8 km from Stop 20 we turn right, continue for another 2.8 km past The Oasis Roadhouse to the Lynd road junction, and then veer to the right onto the Gregory Highway.

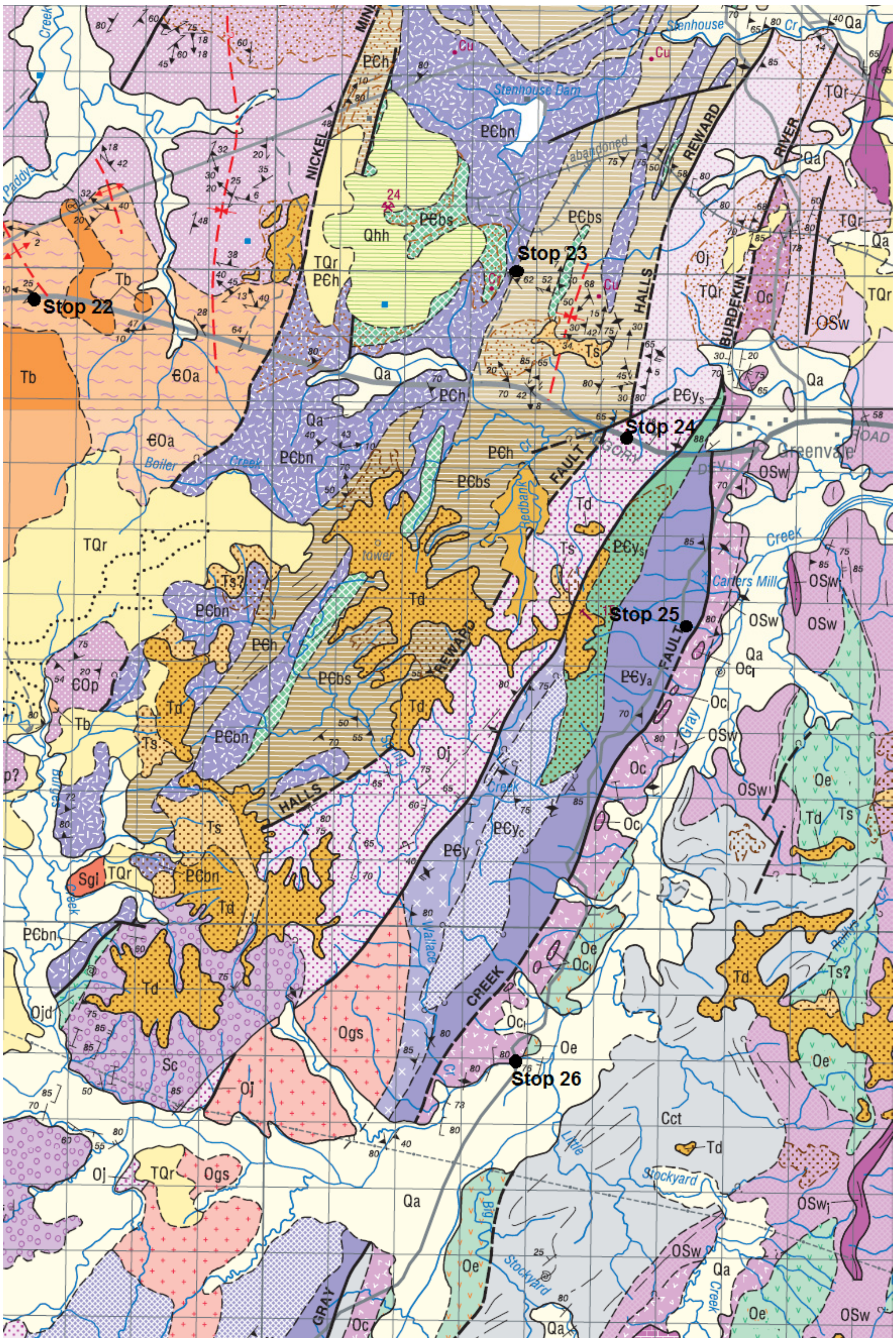
Strongly weathered gneiss, schist and amphibolite of the Oasis Metamorphics and granitoids of the Early Ordovician Lynwater Complex underlie the relatively subdued topography over the next 8 km to where we drive past a low range of hills that are the southern outcrop extent of the Late Cambrian or Early Ordovician Balcooma Metavolcanic Group, a suite of deformed, amphibolite facies felsic volcanics and sedimentary rocks. They are correlated with the Seventy Mile Range Group that occurs in the Charters Towers Province and hosts significant volcanic-hosted sulphide deposits. The Balcooma Metavolcanic Group hosts similar deposits, mined by Kagara Zinc at Balcooma about 20 km to the north.

The Balcooma Metavolcanic Group is bounded on its western side by the Balcooma Mylonite Zone. It has been interpreted as a west-over-east thrust, although sinistral transcurrent movement is also evident from shear-sense indicators.

Stop 21: Gregory Highway, 9.2 km south-east of The Lynd Junction, UTM 55K 249325 7904850, Figure 31

In the cutting near here, the contact between and felsic metavolcanic and metabasalt of the Balcooma Metavolcanic Group and the Early Silurian Dido Tonalite is exposed. Porphyritic metarhyolite, very fine-grained metasandstone and muscovite schist with andalusite porphyroblasts are exposed on the ridge to the north of the road.

The metavolcanic belt is relatively narrow at this point and is intruded out by the north-north-east trending Dido Batholith, which is about 13 km wide. It is strongly weathered and rarely exposed along the road. About 20 km from the Lynd Junction we again cross the ‘Great Dividing Range’. The prominent mesas are of lateritised sediments and regolith derived from the Dido Tonalite. To the east, the country is more dissected and outcrop is better. The rocks are assigned to the Lucky Creek Metamorphic Group, and include the Lugano Metamorphics (a succession of metasedimentary rocks and tholeiitic metabasalt and amphibolite) that is bounded to the east by the Eland Metavolcanics and then Paddys Creek Phyllite. Their age and relationships are not certain, but the rocks are probably Cambrian or Ordovician and may also be correlatives of the Seventy Mile Range Group.


Stop 22
Stop 23
Stop 24
Stop 25
Stop 26
NICKEL
HALLS
REWARD
FAULT
BURDEKIN
RIVER
GRAY
CREEK
Greenvale
Carters Mill
Stenhouse Dam
Stockyard
abandoned
Boiler
Creek
ROAD

Stop 22: Gregory Highway, 1 km east of Paddys Creek, UTM 55K 276250 7899650, Figure 34

The Eland Metavolcanics consist mostly of volcaniclastic rocks of andesitic to dacitic composition with calc-alkaline affinities. They are strongly deformed and metamorphosed to chloritic and actinolite schists and characterised by shallowly dipping foliation and stretching lineations. The rocks at this site do not preserve any of the clastic features, possibly because they were originally finer grained or perhaps because the deformation is more intense and relict fabrics have been destroyed. The rocks have a very strong platy foliation that dips shallowly to the north-west and have a westerly plunging stretching lineation. Crenulations plunge to the north and are related to open folds that deform the Eland Metavolcanics regionally.

Fergusson & others (2007) argued that the low-angle foliation developed by dominantly pure shearing (i.e. ductile flattening) in an extensional crustal environment. Subsequent contractional deformation in the early Silurian resulted in rotation of the low-angle foliation to steeper dips. A subduction-related, Late Ordovician island arc represented by a narrow belt of calc-alkaline volcanic rocks and volcaniclastic strata represented by the Everetts Creek Volcanics and Carriers Well Formation at the western margin of the Camel Creek Subprovince south of Greenvale may have been accreted at this time (Henderson & others, 2011).

Stop 23: Access road to former Greenvale lateritic nickel mine, 1.75 km from the Gregory Highway, UTM 55K 283600 7899900, Figure 34s

The Halls Reward Metamorphics form a metasedimentary tract on the edge of the Greenvale Province. Weathered outcrops at this site consist of mica schist with a weak crenulation. The grade is amphibolite facies and is noticeably higher than the Eland Metavolcanics examined at Site 14, from which they are separated by the Nickel Mine Fault. The fault is interpreted as a westerly dipping structure based on seismic data (Korsch & others, in press).

The metamorphic rocks have a Neoproterozoic or Early Cambrian protolith age, based on detrital zircons, and they were deformed in the Middle Cambrian (520–500Ma; Nishiya & others, 2003). This event correlates with the Delamerian Orogeny in southern Australia and probably predates the Eland Metavolcanic and associated rocks in the Lucky Creek Metamorphic Group.

The Halls Reward Metamorphics are associated with mafic-ultramafic rocks (Boiler Gully Complex), which may represent an early Palaeozoic ophiolite, although the exact relationships and mode of emplacement of these rocks is uncertain. Serpentinite that forms part of this complex, and which has weathered to form the nickeliferous laterite that was worked in the nearby mine, crops out on the hill opposite and can be examined if there is time. It consists of massive greyish green serpentinite with some metagabbro layers and veined with chalcedonic silica.

After returning to the main road it is only 4.8 km to Greenvale township. Points of note include the following: the eastern margin of the Halls Reward Metamorphics is at Redbank Creek, where phyllonite derived from the metamorphics separates them from a belt of quartzose sandstone and strongly cleaved mudstone of the Early Ordovician Judea Formation, basement to the Silurian–Devonian Broken River Province. We may make a quick stop here if there is time.

Figure 34 (opposite): Geology of the Greenvale area. Units are: ⱣꞒh – Neoproterozoic or early Cambrian Halls Reward Metamorphics, units prefixed by : ⱣꞒb – Boiler Gully Complex (n = amphibolite, metagabbro and clinopyroxenite, s = serpentinite), : ⱣꞒ – Gray Creek Complex (subscript s = serpentinite, c = clinopyroxenite, a = amphibolite); ꞒOp – Paddys Creek Phyllite, ꞒOa – Eland Metavolcanics, Oj – Judea Formation, Oc – Carriers Well Formation, Oe – Everetts Creek Volcanics, OSw – Wairuna Formation, Cct – Venetia Formation, – Tb – Miocene nephelinite, Td – laterite, Ts – Paleogene sediments, TQr – Neogene residual soil and colluvium, Qa – alluvium. From Conjuboy and Burges 1:100 000 Geological Sheets. Note that there are some slight differences in colour shades and patterns between the map sheets. Grid squares are 1 km.

Stop 24: Gregory Highway, 2.5 km west of Greenvale township, UTM 55K 285300 7897550, Figure 34

Strongly deformed, thin beds of fine-grained quartzose sandstone and phyllitic mudstone of the Judea Formation exposed in the cutting are tightly to isoclinally folded with a strong cleavage, and are commonly boudinaged. The axial plane cleavage in some of the fold hinges appears to be a crenulation cleavage, possibly related to the regional D_1 folding event. The sandstone beds are strongly veined by quartz along cross-fractures perpendicular to bedding. The Judea Formation is considered to be part of the Thomson Orogen and is basement to the Silurian–Devonian succession of the Graveyard Creek Subprovince of the Broken River Province. It is Early Ordovician. Several dykes of strongly sheared (schistose) quartz-feldspar porphyry up to 50 cm wide occur in one part of the cutting. Low to moderate- angle faults cut the vertical beds and show both east-over-west and west-over-east thrust movement.

About 1 km east of Redbank Creek these rocks are faulted against another serpentinite body that is part of the Gray Creek Complex and forms Lucknow Ridge which is also capped by nickeliferous laterite (see below).

Overnight Greenvale

Greenvale was built to service the former Greenvale nickel mine. Opencut mining of the laterite commenced in 1974, and ceased in 1992. Total production was 428 762t of nickel and 35 776t of cobalt. The main orebody was developed on the serpentinite in the Boiler Gully Complex. The deposit was formed by oxidation and leaching of serpentinite, and the redistribution and concentration of its metal content (originally about 0.3% Ni and 0.01% Co) by migrating acidic groundwater under sufficiently balanced rates of weathering and erosion. The orebody consisted of weathered serpentinite (saprolite) overlain by limonitic laterite. The base-of-ore was very irregular and the zone was typically 5 to 10 m thick. Nickel grades averaged 1.2 to 1.4% but grades of 3% Ni were common. Cobalt grades were low and averaged about 0.25%.

The Greenvale deposit has undergone recent, extensive re-appraisal by Metallica Minerals and has an Indicated and Inferred Resource of 37.7Mt at 0.81% Ni and 0.05% Co, at a 0.5% Ni Cut-off grade. During this most recent work, the laterite on Lucknow Ridge has been found to contain reserves of scandium. Scandium oxide is a critical component of solid oxide fuel cells.

After the mine closed the houses were sold off as low-cost housing options. Some of the residents work in nearby mines such as Balcooma. The hotel is named from a song, *Three Rivers Hotel,* by well-known Australian Country and Western singer the late Slim Dusty, and written by Stan Coster. The hotel in the song was actually the relocatable "Wet Mess" at the Thiess Brothers construction camp for the Greenvale railway where Stan Coster was a grader operator. The hotel has memorabilia of both Stan Coster and Slim Dusty.

Day Six

South of Greenvale

We will drive south of Greenvale along the road to Lucky Springs and Wandovale to examine a package of rocks referred to as the Lucky Springs association and documented by Henderson & others (2011), and interpreted as a Late Ordovician island arc that was accreted to during the early Silurian Benambran Orogeny. It represents the westernmost and probably oldest package within the Camel Creek Subprovince of the Broken River Province (Withnall & Lang, 1993; Withnall & others, 1997a).

Stop 25: Spring Creek causeway near Lucky Springs homestead 6.2 km south from Greenvale, UTM 55K 284930 7892040, Figure 34

The rocks cropping out at the causeway and downstream for about 50 m consist of mylonitised amphibolite of the Gray Creek Complex in the Gray Creek Fault Zone. The mylonite is a black, fine-grained, strongly foliated rock consisting of acicular amphibole (actinolite) and clinozoisite. A subhorizontal mineral lineation is developed in the foliation, which strikes north-north-east and locally anastomoses around less-deformed cores of amphibolite. Complex mesoscopic folds and refolds occur in the zone. The contact with the Carriers Well Formation is sharp, and marked by a few metres of non-outcrop. At the contact the Carriers Well Formation consists of sheared andesitic breccia containing pods of oolitic limestone.

The foliation in the Carriers Well Formation is less intense and much lower in metamorphic grade. Therefore the mylonitised amphibolite formed at a deeper crustal level under ductile conditions, and was juxtaposed against the lower grade rocks during movement on the Gray Creek Fault.

Floaters of the unmylonitised amphibolite and clinopyroxenite can be seen in the creek bed. Mylonitised zones become progressively less abundant within 100 m from the causeway, and the outcrop consists of metagabbro and amphibolite. The amphibolite locally has a foliation locally folded by F_2 folds with an axial plane foliation defined by hornblende. About 500 m upstream, the amphibolite and metagabbro are interlayered with clinopyroxenite and serpentinite.

The Carriers Well Formation is well-exposed along Spring Creek downstream for 1 km from the fault to Gray Creek. It is a strongly disrupted assemblage of volcanic breccia and volcanilithic sandstone with pods of locally oolitic limestone up to 10 m long. The limestone is mainly in the first 500 m of the section. The breccias are poorly sorted and consist of angular clasts of green to purple volcanic rocks, chert and siltstone in a fine-grained, green, chloritic matrix. They were probably deposited as debris flows. Clasts are generally pebble to cobble size, but some slabs of chert are up to 1 m long. It is difficult to determine whether the intercalation of the volcanilithic rocks and limestone is due to tectonic disruption or whether the sequence is a tectonised olistostrome. The rocks have a strong foliation, particularly adjacent to the Gray Creek Fault. Younging reversals indicate that the sequence is folded, but no overall younging direction can be determined. Tight, mesoscopic folds occur in some outcrops.

Figure 35 (left). Volcaniclastic conglomerate interbedded with purple volcanilithic siltstone and fine-grained sandstone in the Carriers Well Formation at Stop 26. Note the boulder that exceeds the width of the bed that contains it.

Figure 36 (above). Thin-bedded quartzose turbiditic sandstone and mudstone in the Wairuna Formation at Stop 27.

Stop 26: Dinner Creek bridge, 11 km south from Greenvale, UTM 55K 283840 7887980, Figures 34 and 35

Continue south for 4.8 km to the grid-type bridge over Dinner Creek. On the upstream side of the bridge, purple to cream, thin-bedded, very fine to coarse-grained volcanilithic sandstone, volcanic breccias, mudstone, chert and mafic to intermediate volcanics of the Carriers Well Formation crop out. The sandstone beds are graded and locally have flame structures and load casts, and young to the west. A weak slaty cleavage occurs in the mudstone. Interbedded with the sandstone are thin to medium beds of breccias which are poorly sorted and consist of angular volcanic and chert clasts. The conglomerates are poorly sorted and consist of angular volcanic and chert clasts. The volcanic rocks are purple and aphyric to feldspar-phyric, and are probably andesite or dacite. Clasts are generally pebble-size, but some beds have boulders that are thicker than the beds in which they occur. The volcanic breccia beds were probably deposited as debris flows, and the arenites are turbidites from a volcanic source.

Downstream from the bridge for about 200 m is a weathered chaotic sequence of feldspar-phyric volcanic clasts in a muddy to sandy matrix. These may be olistostromal deposits or debris flows. Some primary crystal-lithic tuff, graded beds of volcanilithic sandstone and chert also crop out.

For the next 300 m downstream to the junction with Gray Creek, outcrop consists mainly of aphyric, green to purple, spilitised basalt mapped as the Everetts Creek Volcanics. Pillows and calcite-filled amygdales occur locally. Minor feldspar-phyric basalt or andesite, and cobble to boulder-sized, fragmental, mafic rocks also crop out.

Greenvale to Charters Towers

We return to the Gregory Highway and continue to the south-east through the Camel Creek Subprovince of the Broken River Province. These rocks are dominated by turbiditic facies similar to those in the Hodgkinson Province in the Chillagoe area. However, limestone is restricted to sporadic allochthonous blocks up to 2 km long and clasts in conglomerate. Belts of alternating quartz-rich and labile (lithofeldspathic to feldspathic) turbidites have been delineated and are interpreted as stacks of thrust sheets steepened to vertical by later deformation. Younging directions are dominantly to the west and the rocks overall become younger to the east suggesting that the thrust belt verged to the east.

Stops 30, 31 and 32 will be optional depending on time.

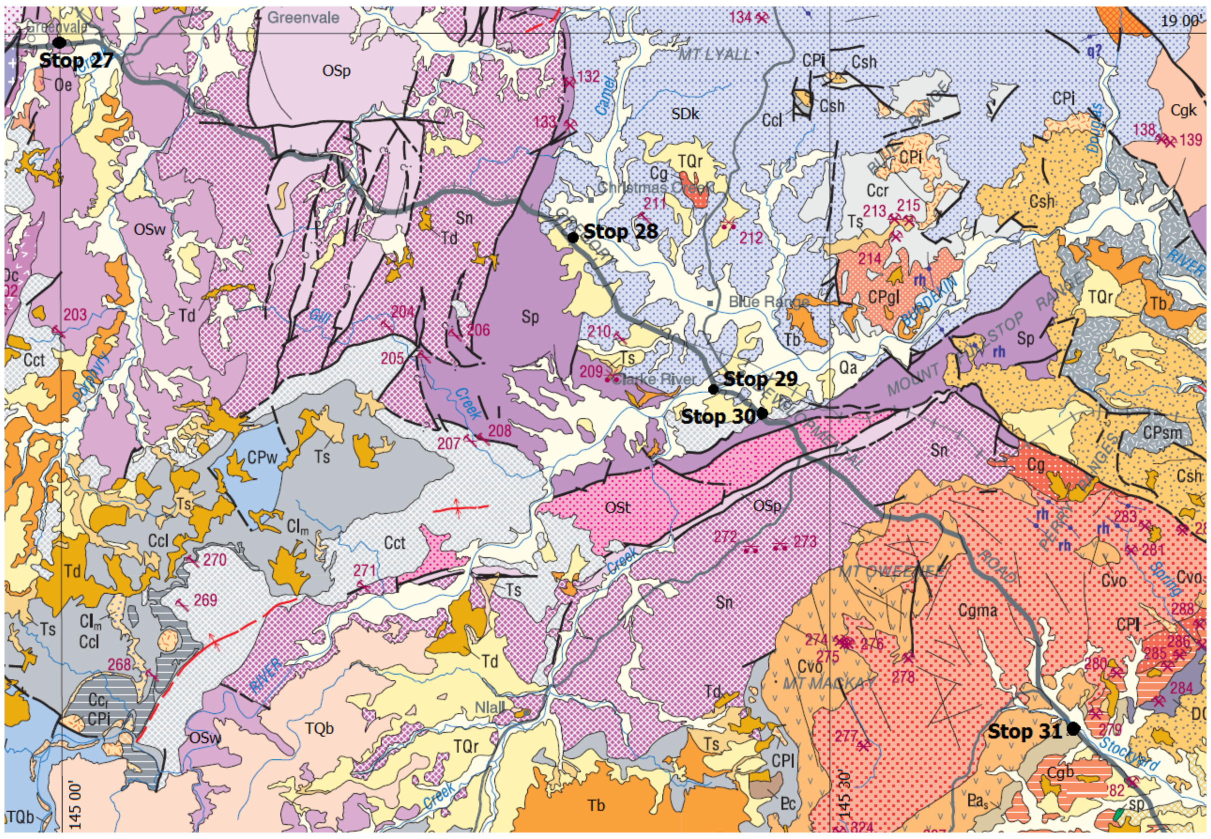


Figure 37: Geology of the Camel Creek Subprovince. Units are: Qa – alluvium, TQr – colluvium, TQb – younger basalt, Tb – older basalt, Td – laterite, Ts – sediments, CPw – Wade beds, CPsm – Marshes Creek beds, Csh – Hells Gate Rhyolite, CPi – felsic intrusives, CPgl, Cg – unnamed granites, Cgk – Kallanda Granite, Cgb – Baumans Camp Granite, Cgma – Malmesbury Microgranite, Cvo – Oweenee Rhyolite, Ccl – Lyall Formation, Cct – Venetia Formation, Ccr – Ruxton Formation, SDk – Kangaroo Hills Formation, Sp Perry Creek Formation, Sn – Greenvale Formation, OSt – Tribute Hills Arenite, OSp – Pelican Range Formation, OSw – Wairuna Formation, Oc – Carriers Well Formation, Oe – Everetts Creek Volcanics, Ꞓc – Cape River Metamorphics, Ꝑa_s – Argentine Metamorphics, sp – serpentinite. From Townsville Hinterland 1:500 000 Geological Map. The lines of longitude are approximately 50 km apart

Stop 27: Cutting on the Gregory Highway, 100 m east of Redbank Creek, about 1 km east of Greenvale township, UTM 55K 289000 7897770, Figures 36 and 37

This cutting is typical of the quartzose turbidites in the Wairuna Formation. Thin to medium-bedded, fine to medium-grained quartzose sandstone and mudstone is complexly folded by at least two generations of folds. Tight folds (some of which could be slump folds) are refolded by more open, upright folds with shallow plunges. In places the tight folds become dismembered, and the rocks are strongly disrupted towards the western end of the cutting.

Continuing east, the first part of the route passes through the Wairuna Formation, a heterogeneous package of quartzose turbidites as above and also altered basalt. At Porphyry Creek, we pass into the Greenvale Formation, a package of lithofeldspathic turbidites. The facies range from very thick amalgamated massive sandstone beds (some of the road cuttings show no obvious breaks over more than 30m) to alternating thin to medium sandstone and mudstone showing classic Bouma structures. The topography of the Greenvale Formation is relatively subdued, contrasting with the Pelican Range Formation which consists of quartzose sandstone like the Wairuna Formation and forms hillier topography. The units are unfossiliferous and the ages poorly known. Detrital zircons in volcanilithic sandstone and zircon in rhyolite pebbles have recently been dated by SHRIMP U–Pb as mid-Silurian (Henderson & others, 2011). These rocks are more typical of the Greenvale Formation. The quartzose turbidites of the Wairuna and Pelican Range Formations may be Ordovician like the Judea Formation.

Stop 28: Gregory Highway, about 46 km from Greenvale, UTM 325200 7883900

Due to time constraints, we will only pause briefly here. A line of limestone bluffs north of the road extend north-north-west for about 500 m. The limestone bodies are entirely surrounded by colluvium so that their exact relationships are not certain, but they are probably part of the Perry Creek Formation. A 2 km-long limestone block in the Perry Creek Formation further along strike has been quarried for aggregate. The blocks are interpreted as olistrostromes. The limestone has few fossils, but the Silurian conodonts and the chain coral, *Halysites* have been found.

East of here the road passes over relatively subdued topography of the Kangaroo Hills Formation, which is Late Silurian to Early Devonian, based on the ages of limestone clasts in conglomerate. Sandstones are generally less lithic than the Greenvale Formation.

Stop 29: Kangaroo Hills Formation at the Clarke River bridge, 57 km south-east from Greenvale, UTM 55K 334850 7874250, Figures 37, 38 and 39

Typical turbidites of the Kangaroo Hills Formation are exposed in the cutting at the southern end of the bridge and in the river bed. Thin to medium-bedded, fine to medium-grained labile sandstone is interbedded with grey mudstone. The sandstones have BC Bouma structures (planar laminae and well-developed convoluted laminae indicating younging to the east-south-east). A weak slaty cleavage is present in the mudstone and the bedding is commonly dislocated by small-scale thrust faults at a low angle to bedding. The thrusts locally form small-scale duplex structures (Figure 38).

A large outcrop about 100 m upstream of the bridge consists of thick to very thick-bedded medium to coarse-grained lithofeldspathic sandstone abruptly overlain by the thin-bedded (more distal) facies. The sandstones are massive to laminated, but cross-bedding is locally present (Figure 39). Facies variations such as here are common throughout the Kangaroo Hills Formation and are interpreted as alternation of proximal and distal turbidites, formed as lobes prograded and then channels were filled and abandoned.

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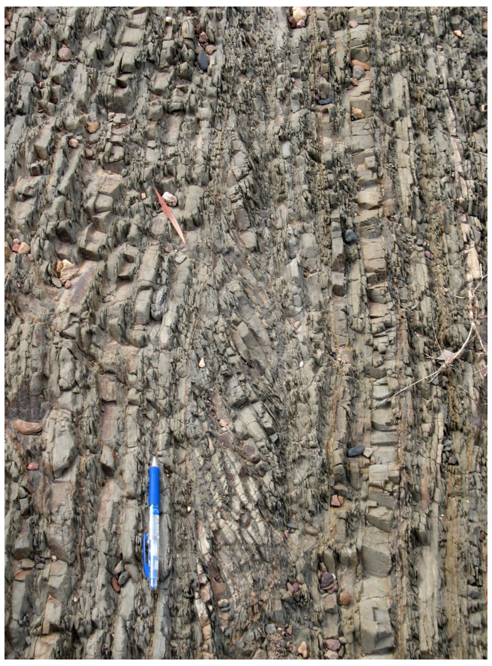

Figure 38 (left): Thin-bedded sandstone and mudstone showing a small-scale duplex structure. Kangaroo Hills Formation, near Clarke River bridge

Figure 39 (above): Cross-bedded lithofeldspathic sandstone. Kangaroo Hills Formation, upstream of Clarke River bridge..

Stop 30: Gregory Highway near the turnoff to Fullstop homestead, 3.6 km from the Clarke River, UTM 55K 337800 7872400, Figure 37

A cutting opposite the turnoff exposes matrix to clast supported conglomerate consisting predominantly of pebbles and cobbles from the underlying units (Perry Creek Formation, Kangaroo Hills Formation, and Tribute Hills Arenite) in addition to jasper and quartz. The matrix is very coarse-grained sandstone. The conglomerate is very thick-bedded and massive here, but in outcrops in adjacent gullies, bedding is defined by alignment of weakly imbricated, elongate clasts. Dips are shallow (< 15°).

The conglomerate forms an elongate belt up to 1 km wide and about 8 km long. It is equated with the basal part of the Mississippian Clarke River Group and is interpreted as valley-fill or an alluvial fan. It postdates the D_2 event in the Camel Creek Subprovince.

South from Stop 30, the highway passes through a series of hills for about 4.5 km. These are a repetition of the Perry Creek Formation, Pelican Range Formation and another quartzose unit, Tribute Hills Arenite, on the south-eastern limb of a large D_2 oroclinal structure that is a feature of the Camel Creek Subprovince. Beyond these hills, the road traverses about 5 km of gently undulating topography underlain by the Greenvale Formation, before entering another hilly section for about 25 km, composed of the coarsely porphyritic Carboniferous Malmesbury Microgranite and coeval, crystal-rich rhyolitic ignimbrite (Oweenee Rhyolite) of the Kennedy Igneous Association.

Stop 31: Gregory Highway near the Ewan Racecourse, UTM 55K 359200 7851400 7872400, Figure 37

A low cutting here exposes grey, fine-grained quartzite and muscovite schist of the Argentine Metamorphics. The schist has a strong platy foliation (probably a finely differentiated crenulation cleavage) and a weak lineation. The rocks are probably late Neoproterozoic or Cambrian like the Halls Reward Metamorphics near Greenvale. They indicate that we have passed out of the Broken River Province into the Charters Towers Province, but the contact, which elsewhere is marked by the Clarke River Fault, is intruded and obscured by the Malmesbury Microgranite and Oweenee Rhyolite.

Rhyolite, possibly part of a dyke, occurs at the western end of the cutting.

From here for about 20 km we drive over Neogene and Quaternary deposits of sand and clay that probably overlie early Paleozoic granitoids and metamorphic rocks. At the Basalt River, we encounter lavas from the Nulla Basalt Province, another of the Neogene to Quaternary volcanic fields of north Queensland. The basalt continues for about 60 km towards Charters Towers, although underlying redbeds of the Late Devonian Dotswood Group are exposed in Breakneck Creek about 36 km from the Basalt River. About 5 km further on at Fletchers Creek, the road crosses the youngest flow of the Nulla Province, the Toomba Flow, which is about 14 000 years old.

About 11 km from Hann Creek and the last of the basalt outcrops, road cuttings begin to show weathered Ordovician to Early Devonian granitoids of the Ravenswood Batholith and metasediments of the Charters Towers Metamorphics that also are part of the Thomson Province and probably late Neoproterozoic or Cambrian. They mainly form large screens within the Ravenswood Batholith.

Stop 32: Gregory Highway, 6 km north of Charters Towers, UTM 55K 419900 7785600, Figure 40

Depending on time, we may stop briefly here to examine a cutting in the Charters Towers Metamorphics. In this cutting, weathered muscovite-biotite schist is cut by folded and foliated leucocratic granite veins.

Stop 33: Towers Hill, Charters Towers, UTM 55K 421850 7778540, Figure 40

On arriving at Charters Towers, we will go to the lookout on Towers Hill for a panoramic view of the town and the surrounding countryside. The rocks exposed on the hill are of the Ordovician Towers Hill Granite, a fine- to medium-grained biotite granodiorite to granite. It also contains minor hornblende. The lower-lying country at the foot of the hill and through much of the city area is hornblende-biotite tonalite of the late Silurian Millchester Creek Tonalite, although a mixture of Ordovician granitoids, Cambrian diorite and Charters Towers Metamorphics also occurs.

We will also stop near the foot of the hill to observe one of the few remaining mullock dumps of the former goldfield. At the mine dump, one of very few that was not reprocessed by cyanide treatment, chlorite–sericite–hematite alteration and disseminated pyrite is apparent. Hematite is a microcrystalline phase which reddens feldspar. Elsewhere epidote may form part of the alteration assemblage.

Gold was discovered in the vicinity on Christmas Eve, 1871 by a four-man prospecting party and the discovery is popularly attributed to an aboriginal youth, Jupiter Mosman. The party quickly located several gold-bearing quartz veins and registered their claims at Ravenswood, an already established goldfield, located towards Townsville. The mining warden at Ravenswood, William Charters, marked out the new field. A group of prominent granite hills that includes Towers Hill were initially named Charters Tors after him, but this was changed to Charters Towers and the name given to the new town and the goldfield.

Within months, several thousand miners had flocked to the field based on reports of rich pickings, e.g. 1600 oz of gold wire recovered at the surface from one reef. Progressively the workings extended more deeply, initially constrained by the water table. The Day Dawn, an extensive reef which dips north-north-east under the present town of Charters Towers and a major ore producer for the field, was worked from 1879. The company floated to work it became the first in Queensland to produce gold worth a million pounds. By 1890 shafts had reached depths of 300 m and a stock exchange was established in the town. The Brilliant reef was discovered by wildcat prospecting shaft in 1889 and led to the most prosperous decade of mining activity. The deepest workings of the Brilliant reached a depth of 900 m. and produced 60 tonne of gold. In 1892 cyanide treatment of ore was introduced with the extensive reworking of tailings. At the turn of the century Charters Towers was the second largest city in Queensland with a population of 27 000. A lack of new discoveries, the price of gold and the manpower demands of World War I combined to see effective closure of the field with the deep workings flooded by 1920. The population declined to 7 000, sustained as a service town to the pastoral industry.

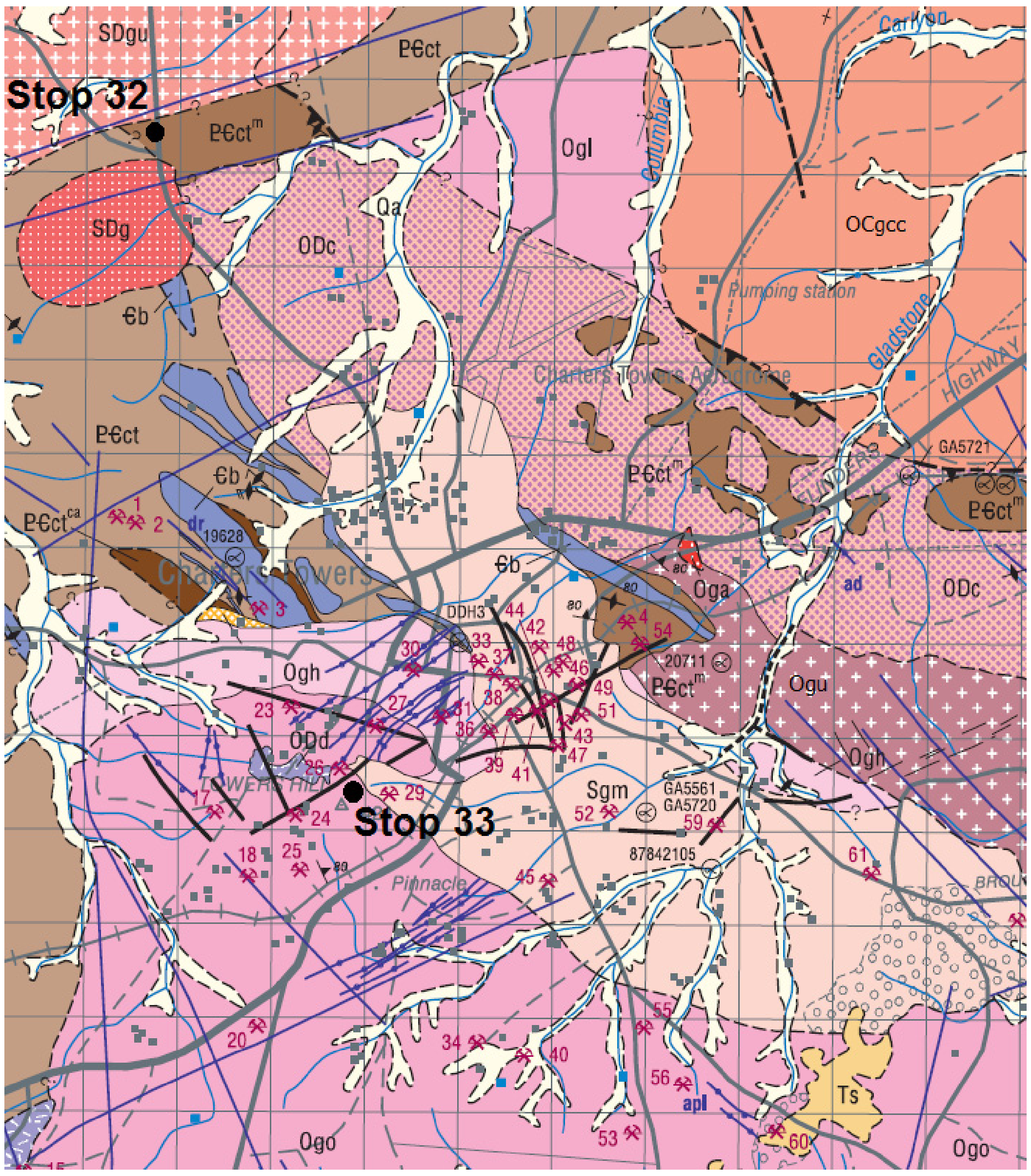

Figure 40. Geology of the Charters towers area. Units are Qa – alluvium; Ts – unnamed sediments; OCgc – Carlyon Complex; SDg – undivided granitoids; SDgu – Urdera Granodiorite; Sgm – Millchester Tonalite; Ogo – Towers Hill Granite; Ogl – Lavery Creek Granite; Ogu – Sunburst Granodiorite; ODc – Columbia Creek Complex; Odd – unnamed diorite; Ꞓb – Bucklands Hill Diorite; PꞒct Charters Towers Metamorphics (PꞒct$_m$ gneissic and migmatitic phases)

Since the 1980s the town has experienced rejuvenation as a gold mining centre, with the working of nearby bulk-tonnage, low-grade subvolcanic Permian breccias at Mount Leyshon hosted by early Paleozoic granitoid and sedimentary rocks and epithermal vein gold at Pajingo hosted by Late Devonian – Mississippian volcanics and volcaniclastics of the Drummond Basin. In addition, old workings in and adjacent to Charters Towers itself have been reopened by Citigold Corporation Ltd which has also developed an exploratory decline to reach ore at depth beneath the town.

Gold-bearing quartz veins at Charters Towers are up to 4.5 m wide as fracture infill. Grades are variable both between and within veins but ranged to >62 g/t. Ore zones are characterised by the sulphide minerals pyrite, galena, sphalerite and chalcopyrite (10–90% by volume) and are surrounded by zones of wall-rock alteration, commonly 2–3 times the with of associated veins but in some cases much more extensive.

Fluid inclusion data suggest that gold was precipitated from CO_2-poor, low to moderately saline fluids at temperatures between ~240 and 300º C (Peters & Golding, 1989) and crustal depths constrained between 5 and 14 km (Kreuzer, 2005). Geological and geochronological data indicate that mineralisation overlapped with the ages of late Silurian – Early Devonian I-type plutons of the Pama Igneous association that are widespread in the Charters Towers district (Kreuzer & others, 2007; Hutton & others, 1997). Significant enrichment in Te contents of auriferous veins suggests a magmatic contribution to the ore-forming fluids (Kreuzer, 2005). However, despite their association in space and time with igneous rocks, the gold deposits lack an obvious causative intrusion. Moreover, published lead isotope studies indicate that the lead in the ore was not acquired from any of the exposed intrusions. The geological and geochemical data are not compatible with derivation of fluids, metals, and ligands from individual plutons. Similarity of host rocks, ore element associations, alteration assemblages, structural controls, and tectonic settings strongly suggest that the auriferous veins of the Charters Towers goldfield belong to a group of granitoid-hosted lode gold deposits that are generally classified as orogenic.

Charters Towers was an important military base during World War II and on the side of the hill are the remains of bunkers used for ammunition storage. Some of these are used to house an earthquake monitoring station established by The University of Queensland in 1957 and now managed by its Earth Systems Science Computational Centre (ESSCC) and Geoscience Australia.

Charters Towers to Townsville

Travelling east from Charters Towers, we first traverse mainly weathered rocks of the Ravenswood Batholith which contain mainly I-type Ordovician to late Silurian granitoids. Ordovician granitoids are generally more deformed and are assigned to the Macrossan Igneous Association. The later Silurian granitoids form part of the Pama Igneous Association, which forms a belt of plutons and batholiths extending for almost 1000 km from the Charters Towers area through the Georgetown area to Cape York Peninsula. Granitoids of similar age are known in the basement to cover successions further south extending into the Lachlan Orogen. In north Queensland, they are intrude the older terranes to the west of the Silurian to Devonian Mossman Orogen and are considered by some interpretations to represent the roots of a continental magmatic volcanic arc related to a west-dipping subduction zone. In this model, the Broken River and Hodgkinson Provinces represent forearc and accretionary wedge assemblages outboard of the arc.

About 50 km from Charters Towers, near the settlement of Mingela, a large bluff south of the highway, consists of fluviatile, quartzose sandstone of the Collopy Formation and is considered to be a Middle or Late Devonian outlier of the Burdekin Basin, the main southern margin of which is about 20 km to the north. The Collopy Formation overlies the Alex Hills Shear Zone, a broad E–W trending tract of sheared Ordovician granitoid thought to have developed in the Silurian Benambran Orogeny. A small basaltic plug, part of the ~40 Ma Mingela Province, is adjacent to the highway just prior to its steep decent immediately east of Mingela.

Commencing in the vicinity of Reid River, and continuing to Townsville, prominent ranges and hills generally consist of rocks referred to the Kennedy Igneous Association (late Carboniferous – early Permian). Most are intrusives but volcanics are also represented, including the Ellenvale beds which form a prominent hill of layered silicic volcanics to the east of the highway near the Reid River crossing. At the aptly named Calcium, an E–W-trending outlier of the Burdekin Basin nonconformable on Ordovician granodiorite is crossed by the highway adjacent to a prominent limestone dip slope of Middle Devonian Burdekin Formation. It was previously quarried for lime and cement manufacture. The quarries are visible to the west of the highway. Skarns are developed in the succession preserved in the outlier and are related to intrusions of the Kennedy Igneous Association.

Mount Elliot, the prominent upland east of the highway, has an elevation of 1235 m and is the highest feature in the landscape of the Townsville area. It is a stock of mainly biotite granite and some microgranite and is Permian with a Rb–Sr age of ~265 Ma.

Stop 34: Castle Hill, Townsville, UTM 55K 479300 7870550

We end our trip overlooking Townsville from Castle Hill, which represents a small stock of undated biotite granite cut by rare mafic dykes. In the environs of Townsville, the Kennedy Igneous Association comprises a volcanic/plutonic assemblage assigned as late Carboniferous, unconformably overlain by the felsic to intermediate Julago Volcanics which are early Permian, based on elements of the *Glossopteris* flora which occur in interbedded sedimentary intervals.

The Julago Volcanics and older rocks are intruded by granites assigned as mid to late Permian on the basis of K–Ar dates from a stock on Mount Stuart and the granite that forms Magnetic Island of ~255 and ~280 Ma respectively. A swarm of mafic and felsic dykes also cuts the Julago Volcanics and older rocks. It is tentatively assigned as early Permian and thought to be of similar age to the Bowen-Gunnedah-Sydney Basin rift system, which extends for about 1600 km from Wollongong, south of Sydney, to its northern termination about 150 km south of Townsville.

The Hervey and Paluma ranges to the west and north-west of Townsville are a peneplanated upland 600 m above sea level, dissected by erosion. The coastal plain represents another erosional landscape division with a Quaternary alluvial/colluvial veneer standing close to present sea level. Uplands of Kennedy Igneous Association rocks, mainly granites, remain as erosional residuals within the coastal plain. The plateau surface of Frederick Peak immediately to the west of Townsville represents a residual of the peneplanated surface as do the summit heights of Mount Stuart, Cape Cleveland and Magnetic Island. The age of the peneplanated surface is uncertain but basalt plugs truncated by it in the vicinity of Mingela are about 40 Ma old (Stephenson & others, 1980). The peneplain is therefore no older than Oligocene and more probably Miocene. The mechanism involved in its uplift is unresolved, as is generally the case for upland in eastern Australia including the Great Dividing Range.

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